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Pionic atom factory project at RIBF
— Present status and future perspectives —

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Precious information has been provided on the meson properties in nuclear medium by observation of π^--nucleus bound systems, which leads to understanding of non-trivial structure of the QCD vacuum. Our experimental project, pionic atom factory project at RIBF, aims at high precision systematic spectroscopy of pionic atoms to extract pion–nucleus interaction which is known theoretically to have strong relation to the chiral symmetry at a finite density. A new challenge is also in progress for pionic atoms with unstable nuclei.

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1. Introduction

Precision spectroscopy of pionic atoms has been serving precious information on the magnitude of the chiral quark condensate $|\langle\bar{q}q\rangle|$ at the nuclear density ρ_0, which is expected to be reduced compared to that in vacuum [1, 2, 3], through determination of the interaction between pion and nucleus at the lowest energy [4]. Theoretical studies connect the *s*-wave part of the iso-vector pion-nucleus interaction strength to $\langle\bar{q}q\rangle$ at finite density [5, 6], and large overlap between pion wave function and nucleus in deeply bound pionic atoms provides the high accuracy information.

Based on experimental data of the pionic atoms, $\langle\bar{q}q\rangle$ is deduced at the density of $0.6\rho_0$ where the overlap between the pion wave function and the nucleus is converged. The deduced $|\langle\bar{q}q\rangle|$ is extrapolated to $|\langle\bar{q}q\rangle|$ at the normal nuclear density by a linear function indicating a 35 % reduction to $|\langle\bar{q}q\rangle|$ in vacuum [4].

So far the precision of $\langle\bar{q}q\rangle$ at the normal nuclear density is limited by the accuracy of the spectroscopy of pionic atoms in the deduction of the *s*-wave interaction. In most of pionic atoms the *p*-wave interaction appears to have stronger effect than the *s*-wave, and the level shifts by the strong interaction are dominated by the influence of the *p*-wave. In this context, deeply bound pionic atoms that could not be observed by X-ray spectroscopy with stopped pion methods play a particularly important role to improve the precision because the *s*-wave interaction is dominating for them. Naturally, improvement of the accuracy of the *s*-wave interaction requires measurement of such pionic atoms over wide range of isotopes and isotones extracting the iso-vector coefficient separately from other contributions. Careful systematic measurement is necessary for further studies.

2. Pionic atoms with stable nuclei

We are preparing for a series of experiments at RIBF, RIKEN, to pursue systematic measurement of deeply bound pionic atoms in an experimental project, pionic atom factory project (piAF) [7]. The project is setting its goal to a systematic measurement of pionic atoms over wide range of nuclei with the tin and the lead isotopes using the world highest intensity deuteron beam at an energy of 500 MeV available at RIBF.

We make use of $(d,{}^3\mathrm{He})$ reactions to produce pionic atoms near a recoil-free kinematical condition to enhance the formation cross section of pionic atoms. We measure the Q-value of the reaction in a missing mass spectroscopy to deduce the mass of the reaction product. The mass resolution is expected to be ~ 400 keV (FWHM), which is comparable to the previous measurement at GSI. The produced pionic atoms are coupled with a neutron hole state and stay near the ground state, $1s$, $2s$, or $2p$ of pionic orbitals. The high resolution makes it possible to resolve several couplings between the pionic orbitals and the neutron hole states in the spectrum.

We carried out a pilot experiment to confirm the experimental feasibility of pionic atom spectroscopy at RIBF. We employed a high intensity deuteron beam with the intensity of 10^{12}/second and the energy of 500 MeV. We placed a target of ^{122}Sn with the thickness of 10 mg/cm^2 and the width of 1 mm at the standard target position of BigRIPS fragment separator [8]. The BigRIPS was used as a high resolution spectrometer to measure the missing mass of the $(d,{}^3\mathrm{He})$ reactions with the dispersion of about 5000. The emitted ^{3}He is momentum-analyzed by the BigRIPS and measured by a set of tracking detectors placed near a dispersive focal plane.

The particles were identified by two sets of scintillation counters, which measured energy loss of particles and Time-Of-Flight between focal planes, and ^{3}He was identified without any background. Typical trigger rate at the dispersive focal plane was about ~ 50 Hz for ^{3}He and ~ 1 MHz for protons originating in the breakup reaction of incident deuterons at the target. Making use of the difference in the TOF for ^{3}He and protons, we had almost pure ^{3}He trigger at the hardware level.

Figure 1 shows the measured Q-value spectrum at forward 0-1 degree with preliminary acceptance and higher order aberration corrections. The vertical dashed line indicates the pion emission threshold. The strengths in the left side of the line originate in the quasi-free pion emission in the $(d,^{3}\mathrm{He})$ reactions. A nearly flat background is observed in the right side of the spectrum which is due to nuclear excitation without pion production. The peaks in the right side of the threshold and left side of the flat background are due to the formation of pionic bound states. Comparison to the theoretical prediction [9] tells that the overall spectra are in good agreement. The distinct peak near Q-value of -138 MeV is assigned to the formation of $(1s)_{\pi}(3s_{1/2})_{n}^{-1}$ state. Peak structures between -142 and -139 MeV are mainly due to $(2s)$ and $(2p)$ pionic states.

The first experiment has proven the feasibility and the potential of RIBF in pionic atom spectroscopy. In the next beamtime to accumulate statistics, we will make an attempt to improve the experimental resolution mainly by reducing the emittance of the incident beam with careful tuning of the ion beam optics.

2.1 Pionic atoms with unstable nuclei

So far the experimentally observed pionic atoms are limited to stable nuclei. It is known that the density probed by pionic stable nuclei is limited to 0.6 ρ_0 regardless of nuclei [10], and pionic atoms with unstable nuclei serves unique opportunities to study density dependence of $\langle\bar{q}q\rangle$. The distribution of pion is strongly affected by the surface structures of the nuclei. In case of pionic atoms with unstable nuclei, particularly in case of nuclei with neutron skin structures, pion wave function is pushed outward by the skin resulting in the shift of the overlap toward lower densities.

Making use of such properties of pionic unstable nuclei for study of $\langle\bar{q}q\rangle$ at different densities, we need to develop a novel method based on a same type of Q-value spectroscopy in an inverse kinematics using a combination of unstable nuclei beams and a deuterium target.

In the inverse kinematics reactions, we need to consider a totally new experimental setup under the condition that the CM kinematics is kept to be the same as that in the normal kinematics reactions. The Q-value is deduced by the measurement of the emitted ^{3}He energies and angles. The emitted ^{3}He has a very low energy of ~ 60 MeV. The experimental apparatus must be carefully designed so as not to deteriorate the resolution. One of the largest difficulties is that high accuracy is needed for the energy measurement of the ^{3}He. The low energy ^{3}He causes a large energy loss and a large angular deviations in any kind of materials. An active deuterium target is a good solution to establish the principles of the measurement which will be followed by a setup for production experiments using a storage ring.

A conceptual design of the presently developed experimental apparatus is shown in Fig. 2. The apparatus is mainly composed of two parts, an MWDC filled with pure deuterium gas and an array

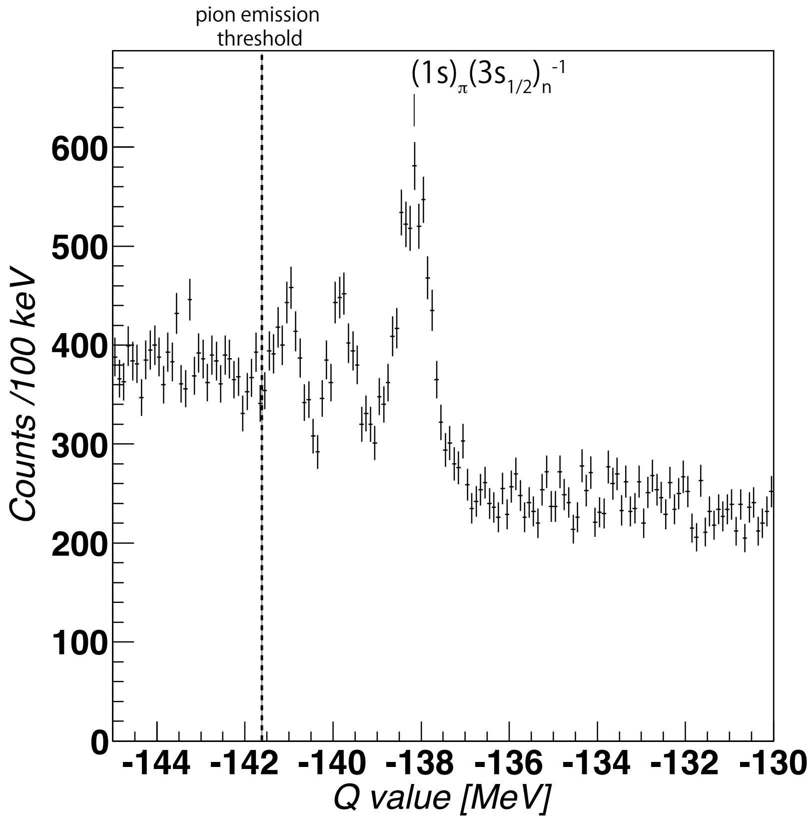

Figure 1: Measured preliminary spectrum of ^{122}Sn$(d,{}^3$He$)$ reaction at forward 0-1 degrees near the pion emission threshold. Momentum acceptance is roughly corrected. The vertical dotted line indicates the π^- emission threshold. A distinct peak near Q-value of -138 MeV corresponds to the formation of $(1s)_\pi(3s_{1/2})_n^{-1}$ state.

of silicon detectors placed in a uniform magnetic field. The MWDC serves not only as a detector to measure the ^{3}He tracks but as an active target for the $(d,{}^3$He$)$ reactions. The incident beam of unstable nuclei reacts with the deuterons in the active target volume and emits ^{3}He. The full energy of the ^{3}He is measured by the silicon detectors. The particles are identified by the energy loss measured in the MWDC, the track radius and the full energy. Hardware trigger is provided by the silicon detectors.

The Q-value resolution in the above setup is estimated to be 500 keV (FWHM) which is comparable to the measurement in the normal kinematics. Main contributions are the resolution of the full energy measured by the silicon detector and the energy loss correction precision based on the vertex lengths. Assuming the active deuterium target volume of 1 meter and ^{132}Sn beam intensity of 10^7/second, total yield in a week of data accumulation will be about 1/10 of that in Fig. 1.

A prototype of the experimental apparatus is in construction and will be tested using stable nuclei beams as a first step.

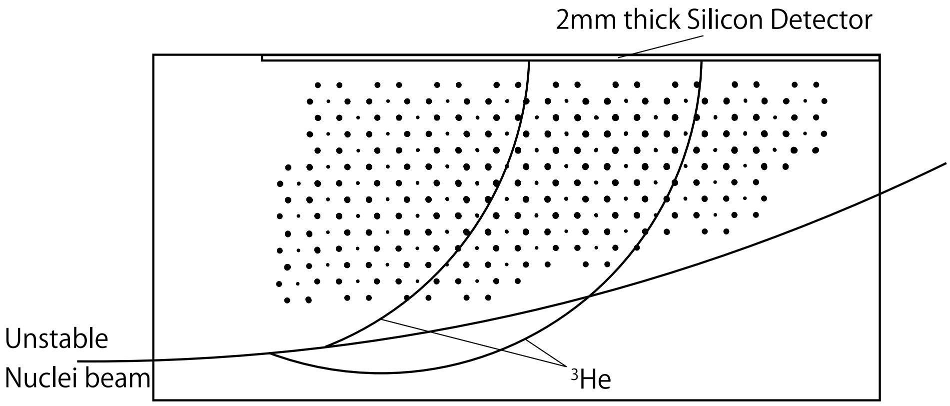

Figure 2: Conceptual design of experimental apparatus for the pionic atom spectroscopy with unstable nuclei in the inverse kinematics reactions. The apparatus is placed in a uniform magnetic field of 1 Tesla. Incident heavy ion reacts with deuterons in the target volume and emits ^{3}He. The ^{3}He tracks and the energy loss are measured by the wires shown by the dots. Full energy of the ^{3}He is measured by the silicon detectors.

3. Summary

An experimental project is ongoing for high precision spectroscopy of pion-nucleus bound systems. Spectroscopy of pionic atoms with stable nuclei is being conducted in RIBF to cover wide range of isotopes. Pionic atoms with unstable nuclei are also in sight.

A characteristic feature of bound-system spectroscopy is that high quality data can be achieved through the measurement of a bound system in well-defined quantum states. Small natural widths compared to the level spacings are essential.

Experimentally a production reaction with small momentum transfer is the key of the spectroscopy to enhance the pionic atom formation cross section and to keep the system stay near the ground levels [4, 11, 12, 13, 14]. In case that the momentum transfer is large and the core nucleus is highly excited, it will become extremely difficult to separately identify the quantum states of the bound system because of the higher density of the levels.

Study of pionic atoms has been reaching a stage of high precision systematic spectroscopy to cover wide range of nuclei which will aid reduction of the ambiguities partly originating from the uncertainties in the properties of nuclei [4, 11, 12, 13, 14]. A pionic atom with even-neutron-number nucleus is also studied theoretically [15]

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