

MESON BOUND STATES SPECTROSCOPY IN NUCLEI: PIONIC ATOMS AT RIBF AND η' -MESIC NUCLEI AT GSI/FAIR*

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Meson–nucleus bound systems have been providing precious information on the meson properties in nuclear medium, which is leading to understanding of non-trivial structure of the QCD vacuum. Two related experimental projects are discussed. One is a pionic atom factory project at RIBF and the other is a spectroscopy of η' -mesic nuclei in GSI/FAIR. The former is aiming at high precision systematic spectroscopy of pionic atoms followed by challenges for pionic atoms with unstable nuclei. The latter is aiming at spectroscopy of η' -mesic nuclei in (p, d) reactions by inclusive and semi-exclusive measurement.

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1. Introduction

Theoretical studies on chiral symmetry breaking in QCD show close relation between hadron properties in nuclei and the magnitude of the chiral quark condensate at finite nuclear density [1, 2]. Precision spectroscopy of meson bound systems with nuclei provides high quality information on the meson properties at the nuclear densities, where chiral condensate is expected to be reduced from that in vacuum [3, 4]. High quality data can be achieved through measurement of a bound system in well-defined quantum states. Small natural widths compared to the level spacings are essential. In this paper, recently developing two cases, pionic atoms [5] and η' -mesic nuclei [6], are discussed.

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In the first case, pionic atoms, a production reaction with small momentum transfer is the key of the spectroscopy to enhance the formation cross section and to keep the system stay near the ground levels [7–11]. In the case when the core nucleus is highly excited, it will become difficult to separately identify the quantum states of the bound system because of the smaller level spacings. Study of pionic atoms has been reaching a stage of high precision systematic spectroscopy to cover wide range of nuclei which will benefit the reduction of the ambiguities partly originating from the uncertainties in the properties of nuclei [7–11]. A pionic atom with even-neutron-number nucleus is also investigated theoretically [12].

In the other case, a new experiment is focusing on discovery of η' -mesic nuclei for which theories predict large binding energies in nuclear matter [13]. The η' meson has remarkably large mass compared with other pseudo-scalar mesons, π , K , and η . Theoretically its large mass is explained by an interplay of $U_A(1)$ anomaly and spontaneously broken chiral symmetry [14]. Accommodating the η' meson in high density medium, nucleus, a large mass reduction is expected due to the reduced chiral condensate in the nuclear medium. Spectroscopy of η' -mesic nuclei will provide stringent constraints to the theories.

2. Spectroscopy of pionic atoms at RIBF

Spectroscopy of pionic atoms provides information on the strong interaction between pion and nucleus at the lowest energies, which leads to the estimation of the chiral condensate $\langle \bar{q}q \rangle$ at normal nuclear density ρ_0 through observation of the modification of the interaction. Theoretically, isovector part of the s -wave interaction changes as $|\langle \bar{q}q \rangle|$ is reduced at the nuclear densities [15–17]. With 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 becomes large. The deduced $|\langle \bar{q}q \rangle|$ was extrapolated linearly to $|\langle \bar{q}q \rangle|$ at the normal nuclear density indicating a 35% reduction to $|\langle \bar{q}q \rangle|$ in vacuum [11].

In spite that the precision of the $\langle \bar{q}q \rangle$ deduction is limited, pionic atoms have been providing unique information on the reduction of the quark condensate at high energy density. For better precision, we need to cover wide range of isotopes and isotones. The process of deducing $\langle \bar{q}q \rangle$ from observation of the iso-vector part of the interaction between pion and nucleus requires careful systematic measurement to extract the iso-vector coefficient from other contributions. Another way is to make a global fit to the existing all pionic atom data. However, in the global fitting procedure, one has to allow strong correlation between parameters. It is not easy to avoid influence among many parameters and to evaluate the uncertainties in the determination of the parameters.

2.1. Pionic atoms with stable nuclei

A series of experiments is in preparation at RIBF, RIKEN as an experimental project of pionic atom factory project (piAF). The project aims at a systematic measurement of pionic atoms over wide range of nuclei in the tin and lead regions on the nuclear chart using the world highest intensity heavy ion beams available at RIBF.

The measurement employs ($d, {}^3\text{He}$) reactions to produce pionic atoms with nearly zero momentum transfer. The Q -value of the reaction is measured in a missing mass spectroscopy to deduce the mass of the reaction product. The missing mass resolution is expected to be ~ 400 keV (FWHM). The produced pionic atoms stay near the ground state, $1s$, $2s$, or $2p$ of pionic orbitals coupled with a neutron hole state. Several couplings between the pionic orbital and the neutron state are resolved and are identified in the spectrum.

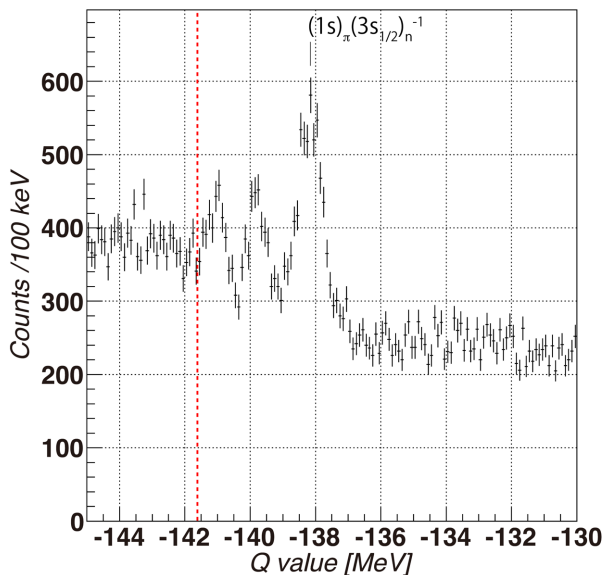


Fig. 1. Measured preliminary spectrum of ${}^{122}\text{Sn}(d, {}^3\text{He})$ reaction at forward 0–1 degrees near the pion emission threshold. The vertical dotted line shows the π^- emission threshold. A distinct peak near Q -value of -138 MeV corresponds to the formation of $(1s)_\pi(3s_{1/2})_n^{-1}$ state. Peak structures between -142 and -139 MeV are mainly due to $(2s)$ and $(2p)$ pionic states.

First experiment was performed to confirm the experimental feasibility of pionic atom spectroscopy at RIBF. A high intensity deuteron beam was employed with the intensity of 10^{12} /second and the energy of 500 MeV.

A target of ^{122}Sn with the thickness of 10 mg/cm^2 and the width of 1 mm was placed at the nominal target station of BigRIPS fragment separator [18] used as a high resolution spectrometer to measure the missing mass of the $(d, {}^3\text{He})$ reactions. The emitted ${}^3\text{He}$ is momentum analyzed by the BigRIPS and by a set of tracking detectors placed near a dispersive focal plane.

Figure 1 shows the measured Q -value spectrum at forward $0\text{--}1$ degree. The vertical dashed line indicates the pion emission threshold. A flat background is seen in the right-hand side of the spectrum, which is due to nuclear excitation without pion production. The continuum in the left-hand side of the threshold is originating in the quasi-free pion emission in the $(d, {}^3\text{He})$ reactions. The peaks in the right-hand side of the threshold are due to the formation of the pionic bound states. Comparing to the theoretical prediction [19], 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.

The first experiment has proven the feasibility and the potential of RIBF in pionic atom spectroscopy. An experiment for full statistics accumulation will follow shortly.

2.2. Pionic atoms with unstable nuclei

In order to study density dependence of $\langle \bar{q}q \rangle$, pionic atoms with unstable nuclei provide unique opportunities. It is known that the density probed by pionic stable nuclei is limited to $0.6 \rho_0$ regardless of nuclei [20]. In the case of pionic atoms with unstable nuclei, the distribution of pion is strongly affected by the surface structures of the nuclei. Particularly in the case of nuclei with neutron skin structures, pion wave function is pushed outward providing sensitivity for lower densities.

For such purposes, a novel method is being developed based on the same type of Q -value spectroscopy in an inverse kinematics using a combination of unstable nuclei beams and a deuterium target. Keeping the same CM kinematics with that in the normal kinematics reactions, Q -value is measured by measurement of the emitted ${}^3\text{He}$ energies and angles. The emitted ${}^3\text{He}$ has a very low energy of $\sim 60 \text{ MeV}$. The experimental apparatus must be carefully designed so as not to deteriorate the resolution. One of the largest difficulties is that the low energy ${}^3\text{He}$ causes a large energy loss and a large angular deviations in 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.

Figure 2 shows a conceptual design of the presently developed experimental apparatus. It is mainly composed of two parts, a deuterium active target MWDC to measure the ${}^3\text{He}$ tracks and an array of silicon detectors to measure the full energy placed in a uniform magnetic field. The incident beam of unstable nuclei reacts with the deuterium in the active target vol-

ume and emits ^3He . The ^3He tracks are measured by the MWDC and the ^3He full energy by the silicon detectors. Hardware trigger is provided by the silicon detectors. Energy loss in the MWDC is also measured for particle identification.

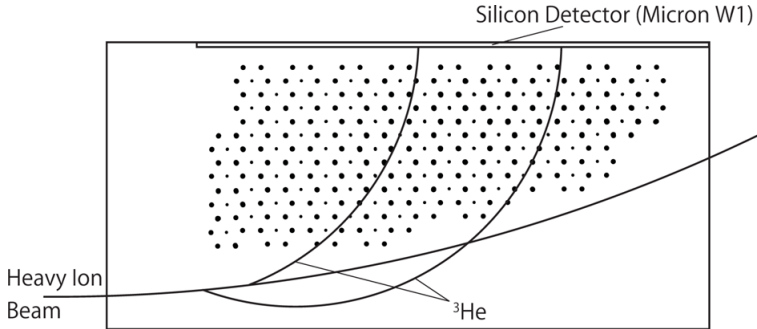


Fig. 2. Conceptual design of the presently developed experimental apparatus for pionic atoms spectroscopy with inverse kinematics reactions. Experimental apparatus is placed in a uniform magnetic field of 1 Tesla. Incident heavy ion reacts with deuterons in the target volume and emits ^3He . The ^3He tracks are measured by the wires shown by the dots. Full energy of the ^3He is measured by the silicon detectors.

Q -value resolution in the above setup is estimated to be 500 keV (FWHM). 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 $10^6/\text{second}$, total yield in a week of data accumulation will be similar to that in Fig. 1.

The experimental apparatus will be tested using stable nuclei beams as a first step shortly. Development of MWDC and a test of silicon detector are in progress.

3. Spectroscopy of η' -mesic nuclei at GSI/FAIR

It may be too early to discuss the detailed properties of η' -mesic nuclei before their discovery. Several theories employ NJL model and predict considerably large mass reduction of η' meson in nuclei, that results in an attractive interaction between η' and nucleus [14, 21, 22].

A series of experiments is in preparation by using (p, d) reaction at $T_p = 2.5$ GeV. The experiments aim at observation of η' -mesic nuclei as peak structures in the Q -value spectrum. Theoretical calculations show the estimated η' -mesic nuclei formation cross section of about 10–50 nb/sr/MeV in (p, d) reaction at $T_p = 2.5$ GeV [13]. The formation cross section is strongly depending on the interaction between η' and nucleus.

3.1. Inclusive measurement at GSI

The first experiment will focus on an inclusive measurement of the (p, d) reaction on ^{12}C target. Figure 3 shows the expected experimental spectrum for a case of attractive potential of $V(r) = (-150 + 5i)\rho(r)/\rho_0$ [MeV] between η' and nucleus, where $\rho(r)$ denotes nuclear density distribution. Peak structures are expected to stand on a large background which is mainly due to multiple pion production in the (p, d) reactions. In the inclusive measurement, the small S/N ratio will require very high statistics in order to observe peak structures. One of the merits of the inclusive measurement is its simple analysis procedure to obtain the experimental spectrum, which naturally excludes unexpected distortion of the spectrum during the analysis.

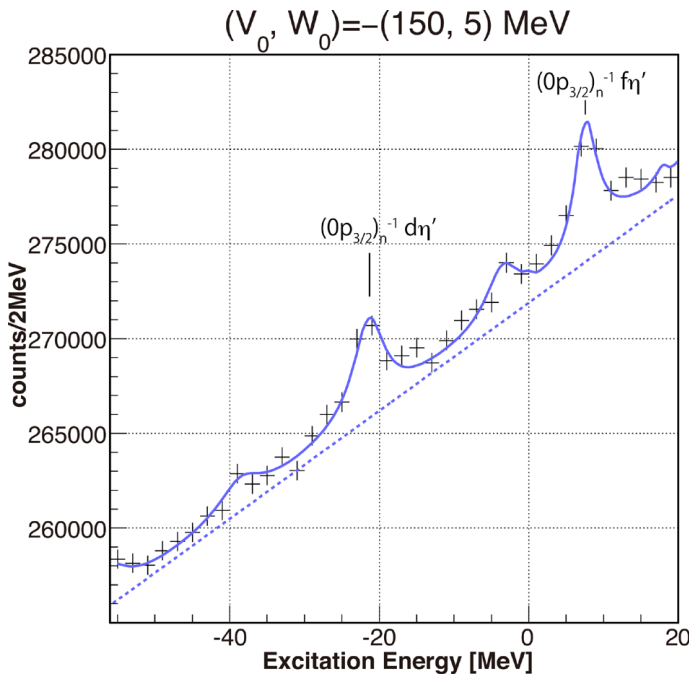


Fig. 3. Simulated spectrum of $^{12}\text{C}(p, d)$ reaction at $T_p = 2.5$ GeV for an attractive potential between η' and nucleus of $V(r) = (-150 + 5i)\rho(r)/\rho_0$ [MeV]. The statistics corresponds to 3.24×10^{14} protons on target of ^{12}C with the thickness of 4 g/cm^2 .

Experiment will be performed at fragment separator (FRS) of GSI [23]. FRS is used as a forward spectrometer with very high resolving power of about 2000. The incident proton beam has a kinetic energy of $T_p = 2.5$ GeV and an intensity of 10^{10} /spill with an acceleration cycle of 6 seconds. The momentum transfer of the $^{12}\text{C}(p, d)$ reaction at $T_p = 2.5$ GeV is 300–500 MeV/ c .

FRS has unique advantages when used as a spectrometer. Its long beam-line of about 72 meters will benefit reduction of instrumental background mainly caused by a high intensity primary beam hitting the beampipe wall in the first sector magnet D1. A set of MWDC detectors will be installed near the final dispersive focal plane S4 to measure the deuteron momenta. Scintillation counters (SC1, SC2) and Cherenkov counters will be used for particle identification and hardware trigger generation.

The above experiment for inclusive measurement is in preparation at GSI and will be scheduled in 2014. An integrity test of the whole detector system will be conducted in January 2014 at COSY facility in FZ-Jülich.

3.2. Semi-exclusive measurement at FAIR

The inclusive measurement has its own advantages in spite that the peak-finding-performance is limited by the small S/N ratio. In fact, even if the discrete quantum states are existing, these states cannot be observed in the inclusive measurement in case that the states have large widths or small cross sections.

Keeping the advantages of the missing-mass spectroscopy, a semi-exclusive measurement will be effective to enhance the S/N ratio. Theories predict several channels for the absorption of η' in nuclei in the decay of the η' -mesic nuclei. Major channels are $\eta'N \rightarrow \eta N$ and $\eta'NN \rightarrow NN$ and a minor channel is $\eta'N \rightarrow \pi N$, where N denotes a nucleon. Among the absorption channels, two nucleon absorption channel $\eta'NN \rightarrow NN$ is promising. The large Q -value of the absorption of ~ 1 GeV is shared by two nucleons which will have a kinetic energy of ~ 500 MeV. Such a high energy proton is rarely observed in other channels. Thus, tagging a high energy proton near the target region will reduce the multi-pion production background effectively.

An experiment for semi-exclusive measurement of (p, d) with high energy proton tagging is in preparation for Super-FRS/FAIR.

4. Summary

Two experimental projects are ongoing for high precision spectroscopy of meson–nucleus bound systems. Spectroscopy of pionic atoms is being conducted in RIBF to cover wide range of stable nuclei. Pionic atoms with unstable nuclei are also in sight. There is an experimental project to make a missing-mass spectroscopy of η' -mesic nuclei in (p, d) reaction at GSI/FAIR. A combination of high intensity proton beam and high resolution forward spectrometer yields high precision and high statistics spectra. For better S/N , a semi-exclusive measurement of (p, dp) is also in consideration.

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