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Spectroscopy of η' -nucleus bound states at GSI and FAIR

— very preliminary results and future prospects —

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Abstract The possible existence of η' -nucleus bound states has been put forward through theoretical and experimental studies. It is strongly related to the η' mass at finite density, which is expected to be reduced because of the interplay between the $U_A(1)$ anomaly and partial restoration of chiral symmetry. The investigation of the $C(p, d)$ reaction at GSI and FAIR, as well as an overview of the experimental program at GSI and future plans at FAIR are discussed.

Keywords η' mesic nuclei · $U_A(1)$ anomaly · partial restoration of chiral symmetry

1 Introduction

It is theoretically argued that the heavy mass of the η' meson, which is around $958 \text{ MeV}/c^2$, originates from the interplay between the $U_A(1)$ anomaly in Quantum Chromodynamics and the spontaneous breaking of chiral symmetry [1]. Furthermore, when chiral symmetry is partially restored at finite density, the mass is expected to be reduced. For example, 150 MeV mass reduction at the normal nuclear density is estimated in the Nambu–Jona-Lasinio model calculation [2], and a recent calculation using the linear sigma model predicts 80 MeV reduction [3]. In the QMC (quark-meson coupling) model, a rather small mass reduction of 37 MeV is predicted for the case of an η - η' mixing angle of -20° [4].

The mass reduction at finite density is, in other words, the outcome of an attractive interaction between an η' meson and a nucleus. If the attraction is strong enough, an η' -nucleus bound state may be formed. For the experimental observation of such a bound state, the decay width is one of the important ingredients. The chiral unitary model including a Lagrangian term which couples the singlet meson to the baryons indicates that the real part of the optical potential is in general deeper than the imaginary part, while the coupling constant is an unknown parameter [5].

From the experimental side, two kinds of measurements, η' photoproduction off nuclei [6] and η' production in proton-proton collision [7], have been used to extract the information on η' -nucleus interaction and η' -nucleon interaction, respectively, by taking different approaches.

The CBELSA/TAPS experiment determined both the real part [8] and the imaginary part [9] of the η' -nucleus optical potential. The imaginary part,

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which is half of the absorption width, was obtained to be 10 ± 2.5 MeV through a measurement of the transparency ratios for different nuclear targets [9]. In addition, by comparing the excitation function and the momentum distribution of η' mesons for the photoproduction off carbon with corresponding theoretical calculations, the real part was derived as $-(37 \pm 10(\text{stat}) \pm 10(\text{syst}))$ MeV [8]. Through these studies, they concluded a possible existence of η' mesic nuclei [6,8].

The near-threshold behavior of the cross section of the $pp \rightarrow pp\eta'$ reaction supplies information on the η' -nucleon interaction. The COSY-11 experiment determined the η' -proton scattering length in free space, as $(0 \pm 0.43) + i(0.37_{-0.16}^{+0.40})$ fm. It indicates a shallow depth of the η' -nucleus optical potential if one assumes no energy and density dependence [7,10].

The investigation of η' mesic nuclei will be an alternative way to extract direct information of the η' -nucleus interaction. We plan a series of missing-mass spectroscopy experiments with the (p, d) reaction [11] at GSI and FAIR. As the first step, we performed an inclusive measurement at GSI. Moreover, a semi-exclusive measurement, with the coincidence of decay particles from η' mesic nuclei, will be studied in the future at FAIR.

2 Inclusive measurement at GSI

η' -mesic nuclei will be produced by impinging a 2.5 GeV proton beam onto a 4 g/cm^2 -thick carbon target. The incident energy is slightly above the η' production threshold in the $pn \rightarrow d\eta'$ reaction. The missing-mass is obtained by analyzing the momentum of the ejectile deuterons with the Fragment Separator (FRS) used as a high-resolution spectrometer. The missing-mass resolution is estimated to be less than $2 \text{ MeV}/c^2$ in σ , which is dominated by the uncertainty of the reaction vertex inside the target. It would be sufficiently smaller than the decay width of η' mesic nuclei, and this feature is one of the advantages of our experiment.

Figure 1 shows a simulated spectrum corresponding to 4.5 days of data acquisition for different η' -nucleus optical potentials parameterized as $V_0 + iW_0$ [11]. In the simulation, the cross section in the (p, d) reaction is assumed to be the sum of a theoretical calculation [12,13], in which η' production is involved, and contributions of background processes of multi-pion production, evaluated from past measurements of proton-nucleon cross sections [?]. The experimental sensitivity of finding peak structures above a huge background will be large enough in case of a large $|V_0|$ and a small $|W_0|$. While the signal-to-noise ratio will be of the order of $1/100$ even in such a case, a high-statistics measurement with an intense primary beam will compensate the poor signal-to-noise ratio.

The first experiment (GSI S-437) was carried out at GSI in August 2014. Figure 2 shows the experimental setup at FRS. Two sets of multi-wire drift chambers (MWDC's) were installed close to a dispersive focal plane at S4, and the momentum of ejectile deuterons could be analyzed by measuring their

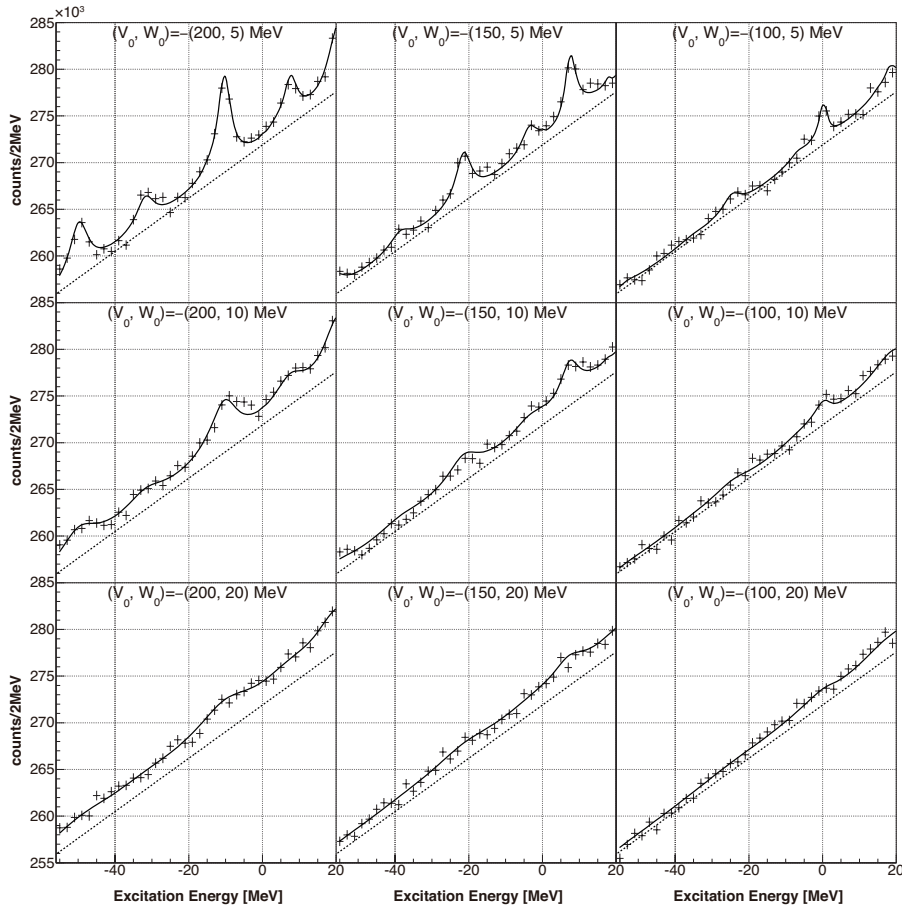


Fig. 1 Simulated spectra with 4.5 days of data acquisition assuming different η' -nucleus optical potentials, parameterized as $V_0 + iW_0$. The dashed line corresponds to the background of quasi-free multi-pion production processes.

tracks with them. For particle discrimination between deuterons and protons from inelastic scattering, we measured the time-of-flight between S2 and S4 by plastic scintillators labelled with SC2H, SC2V, SC41, and SC42. In addition, we prepared Čerenkov detectors with high refractive-index ($n = 1.17\text{--}1.18$) silica aerogel radiators, which were developed at Chiba University [14], (HIRAC and mini-HIRAC) and a total-reflection Čerenkov detector with an Acrylite radiator (TORCH). It is worth emphasizing that we could make the main trigger for the (p, d) reaction with a tight coincidence of the signals of the scintillators in S2 and S4, and without an anticoincidence of these Čerenkov detectors. This removes the influence of a possible position-dependence of the overkill rate of each Čerenkov detector on the missing-mass spectrum.

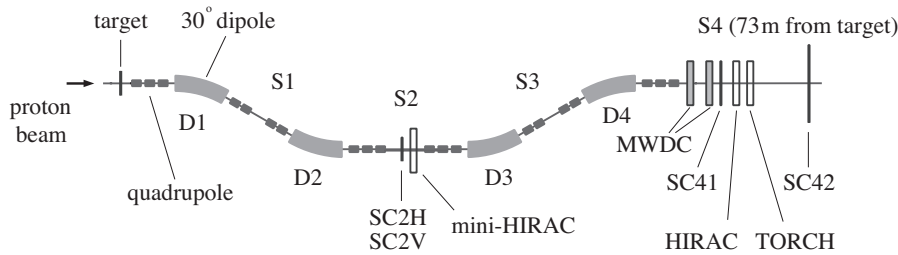


Fig. 2 Schematic view of the experimental setup in August 2014.

Figure 3 shows the TOF distribution between S2 and S4 obtained by an unbiased trigger. The two peaks are ~ 20 ns distant from each other, which is consistent with the TOF difference between protons and deuterons within the momentum acceptance. The deuteron-to-proton ratio is found to be approximately $1/200$. Later on, we could achieve a deuteron-to-proton ratio around unity by tuning the coincidence timing in order to remove the protons on the trigger level. The remaining background, which is seen beneath the deuteron peak in Fig. 3, is due to sequential protons with a short (~ 20 ns) time interval. The waveforms of the scintillator signals will serve to distinguish one-pulse events from two-pulse events. We have been working to improve the purity without losing the efficiency in particle identification.

We have taken data for the following reactions with changing the FRS magnetic field to cover a wide range of excitation energies between -90 MeV and $+40$ MeV relative to the η' emission threshold.

- $^{12}\text{C}(p, d)$ reaction at 2.5 GeV incident energy
- $\text{D}(p, d)$ reaction at 2.5 GeV incident energy (for background study)
- $\text{D}(p, d)p$ reaction at 1.6 GeV incident energy (for calibration)

The analysis of the MWDC's is in progress. For example, the overall missing-mass resolution for the $^{12}\text{C}(p, d)$ reaction has been estimated to be $\sigma \sim 2$ MeV (preliminary) from the missing-mass resolution of the proton peak in the calibration process.

3 Semi-exclusive measurement at FAIR

While we will proceed with an inclusive measurement with higher statistics in a future experiment, another way is to make a coincidence of the forward going deuteron with decay particles from the decay of η' mesic nuclei (semi-exclusive measurement). We aim to tag a proton from the two-nucleon absorption process ($\eta' NN \rightarrow NN$), which is one of the major decay modes of η' mesic nuclei [12]. This proton has a kinetic energy around 300–600 MeV. Such a fast proton will be hardly emitted from the main background of multi-pion production processes, even if rescattering takes place, and the coincidence is expected to improve the signal-to-noise ratio significantly. More quantitative

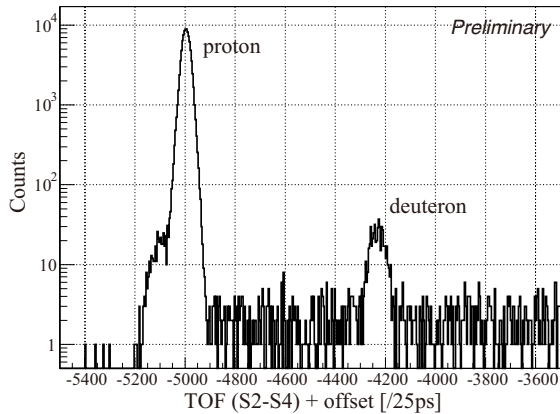


Fig. 3 Time-of-flight distribution between S2 and S4.

evaluation of the proton distribution from the background processes as well as the decay of η' mesic nuclei, by an intra-nuclear cascade simulation using a microscopic transport model JAM [15], is under way.

We plan to develop a proton counter to be installed surrounding the target, by which protons can be distinguished from charged pions. This experimental setup will be possible at Super-FRS, which is to be built in the FAIR complex.

4 Summary

We are investigating η' mesic nuclei by means of missing-mass spectroscopy with the (p, d) reaction. An inclusive measurement of the (p, d) reaction on ^{12}C at FRS/GSI was carried out in August 2014. The expected resolution will be around $2\text{ MeV}/c^2$, which is much smaller than the width of η' mesic nuclei. The analysis is under way.

Furthermore, we plan to perform a semi-exclusive measurement at Super-FRS/FAIR, with tagging decay protons from the two-nucleon absorption process in η' mesic nuclei. The signal-to-noise ratio, which is of the order of $1/100$ at most in the inclusive spectrum, will be improved significantly. A detailed Monte Carlo simulation with a microscopic transport model JAM is in progress.

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