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Spectroscopy of η' Mesic Nuclei via Semi-Exclusive Measurement at FAIR

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Abstract. In order to investigate a possible mass reduction of an η' meson at finite density, a series of missing-mass spectroscopy experiments of η'-nucleus bound states with the ^{12}C(p,d) reaction is planned at GSI and FAIR. A semi-exclusive measurement with the tagging of protons from η' two-body absorption ($\eta' NN \to NN$) will be a key feature in an experiment with Super-FRS at FAIR.

1 Introduction

Experimental investigations of meson-nucleus bound states, namely mesic atoms and mesic nuclei, are very important for a better understanding of hadron-nucleon interaction, hadron-nucleus interaction, and properties of an in-medium hadron, which might be affected by partial restoration of chiral symmetry at finite density. One good example is a missing-mass spectroscopy experiment of deeply-bound pionic atoms by use of the (d,^{3}He) reaction at GSI and RIBF [1]. The existence of mesic nuclei, in which pseudoscalar mesons such as $\overline{K}$, η, and η' are embedded, is predicted theoretically.

In particular, the η' mass at normal nuclear density is expected to decrease by around 150 MeV/c^2, compared with the PDG mass of 958 MeV/c^2, according to the NJL model calculations [2, 3]. This significant mass reduction is the outcome of partial restoration of chiral symmetry, affecting the contribution of the $U_A(1)$ anomaly in QCD to the η' mass [4]. If this is the case, the interaction between an η' meson and a nucleus becomes strongly attractive, and η'-nucleus bound states will exist.

A missing-mass spectroscopy experiment of η' mesic nuclei with the ^{12}C(p,d) reaction is planned at GSI. A primary proton beam with the kinetic energy 2.5 GeV is supplied by the SIS-18 synchrotron,

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and the ejected deuterons will be momentum-analyzed by the fragment separator (FRS) used as a spectrometer. For the details, please refer to Refs. [5, 6].

Furthermore, the investigation with a proton beam can be continued at the Facility for Antiproton and Ion Research (FAIR) [7], which is being constructed next to the GSI site. The superconducting fragment separator (Super-FRS) will enable us to perform a coincidence measurement of particles originating from η' absorption in nuclei, which will improve the signal-to-noise ratio largely.

In this paper, our staging strategy from FRS (GSI) to Super-FRS (FAIR) and the concept of the experiment at FAIR will be described.

2 Inclusive measurement at GSI

The ^{12}C(p,d) reaction will be used to produce η' mesic nuclei $^{11}\text{C} \otimes \eta'$ with the elementary process of $pn \to d\eta'$. In Ref. [8], its double differential cross section $d^2\sigma/d\Omega dE$, where E stands for the excitation energy of an η'-nucleus system, was calculated to be on the order of 10 nb/sr/MeV for the case of a large mass reduction (150 MeV) and a small absorption width ($\lesssim$ 20 MeV)[1].

Meanwhile, the major background in the same reaction arises from quasi-free multi-pion production processes, such as $pN \to d\pi\pi$, $d\pi\pi$, and $d\pi\pi\pi\pi$. By using the cross sections of the corresponding elementary processes, which were obtained on the basis of COSY-ANKE data, the cross section for the ^{12}C target was evaluated to be around 4 μb/sr/MeV [5].

Then, the signal-to-noise ratio in a missing-mass spectrum will be of order 1/100 or less, depending on the mass reduction and the absorption width of in-medium η' mesons, in other words, the η'-nucleus optical potential. In case of a large mass reduction *and* a sufficiently small absorption width, which are supported by the NJL model calculations and the CBELSA/TAPS result, respectively, a peak structure near the η' production threshold will be observed experimentally by a high-statistics and high-resolution measurement[2]. Conversely, when any statistically significant peak structure is not observed, we may be able to discard such a scenario to some extent.

Whatever the η'-nucleus optical potential is, we will be able to obtain the overall structure of the missing-mass spectrum, through an inclusive measurement of the (p,d) reaction with FRS/GSI, from the unbound region to the bound region for the first time. One of the advantages of the inclusive measurement is that no assumption about the η' absorption in nuclei is required in the analysis. Moreover, the knowledge of the inclusive spectrum will be important when considering an upgraded measurement at FAIR, discussed in the next section.

3 Semi-exclusive measurement at FAIR

In order to improve the signal-to-noise ratio, it is essential to carry out a coincidence measurement of emitted particles after η' absorption, i.e. decay particles of η' mesic nuclei. The absorption process can be divided into one-body absorption ($\eta' N \to \eta N$, πN) and two-body absorption ($\eta' NN \to NN$) [8]. Hence the tagging of a proton can be a signature of η' absorption. Figure 1 shows the kinetic energy distribution of protons from each absorption mode. The proton from two-body absorption, which has the largest kinetic energy (300–700 MeV), will be more favorable, because such a fast proton is hardly emitted together with a meson (π or η) even from other background contributions.

Contrary to the signal, the major background of quasi-free multi-pion production does not produce any protons in the primary stage. However, the final state interaction between the produced pions

[1] A recent measurement of the transparency ratio for η' photoproduction by the CBELSA/TAPS Collaboration [9] indicates the absorption width of 15–25 MeV at the normal nuclear density.

[2] The expected spectra for various cases with 3.24×10^{14} protons (corresponding to 4.5-day data acquisition with 10^{10} protons per spill) on a 4 g/cm^2-thick target are shown in Ref. [5].

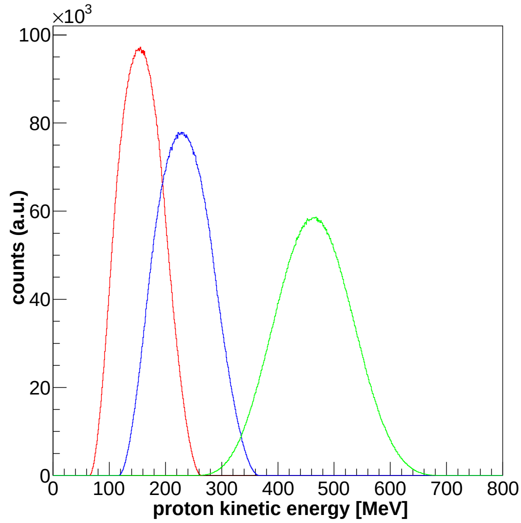

Figure 1. The kinetic energy of protons from η' absorption in a nucleus. The red, blue, and green lines correspond to $\eta' N \to \eta N$, $\eta' N \to \pi N$ (one-body absorption), and $\eta' NN \to NN$ (two-body absorption), respectively.

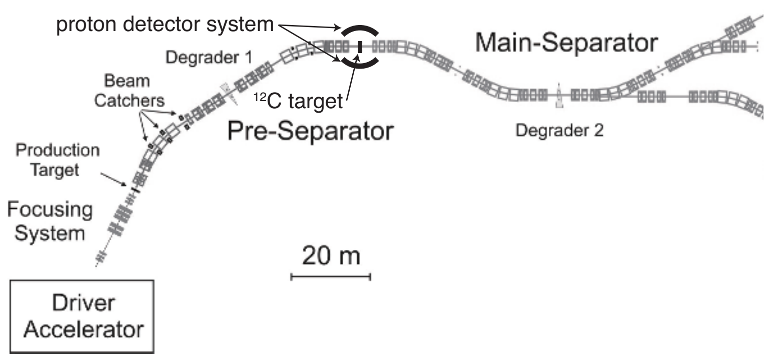

Figure 2. The Super-FRS facility at FAIR.

and the residual nucleus must be taken into account; secondary processes such as pion rescattering and pion absorption can produce a proton in the final state. A quantitative estimation of the proton distribution by a microscopic transport calculation code, JAM [10], is in progress.

The detection of fast protons will be possible by installing a ^{12}C target and surrounding detectors between the pre-separator and the main-separator of Super-FRS (Fig. 2). In case of GSI [5], the target will be located inside a vacuum chamber upstream of the FRS separator (shaped like the main-separator of Super-FRS) and the installation of a detector close to the target is very difficult. While the detail of the detector itself is under consideration, one possibility is to construct a very thick range stack array for distinguishing protons from $\pi^{\pm}$'s. The detector system for the deuteron measurement will be similar to the experimental setup in the GSI experiment, except for a much larger geometrical acceptance.

4 Summary

We plan to carry out a missing-mass spectroscopy experiment of η' mesic nuclei at GSI and FAIR. By using the Super-FRS facility at FAIR, not only an inclusive measurement of the (p,d) reaction, but also a semi-exclusive measurement of the (p,dp) reaction, where the ejected proton is due to η' absorption in a nucleus, will be realized. In particular, the latter measurement is crucial to improve the signal-to-noise ratio. Studies with Monte Carlo simulations for the proton detection have been started, in parallel with the preparation of the first experiment at GSI, which is expected to start in 2014.

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References

[1] T. Nishi *et al.*, in these proceedings.
[2] P. Costa, M. C. Ruivo, and Yu. L. Kalinovsky, Phys. Lett. **B560**, 171 (2003).
[3] H. Nagahiro and S. Hirenzaki, Phys. Rev. Lett. **94**, 232503 (2005); H. Nagahiro, M. Takizawa, and S. Hirenzaki, Phys. Rev. C **74**, 045203 (2006).
[4] D. Jido, H. Nagahiro, and S. Hirenzaki, Phys. Rev. C **85**, 032201(R) (2012).
[5] K. Itahashi, H. Fujioka *et al.*, Prog. Theor. Phys. **128**, 601 (2012).
[6] Y. K. Tanaka *et al.*, in these proceedings.
[7] http://www.fair-center.eu
[8] H. Nagahiro, D. Jido, H. Fujioka, K. Itahashi, and S. Hirenzaki, Phys. Rev. C **87**, 045201 (2013).
[9] M. Nanova *et al.* (CBELSA/TAPS Collaboration), Phys. Lett. **B710**, 600 (2012).
[10] Y. Nara, N. Otuka, A. Ohnishi, K. Nitta, and S. Chiba, Phys. Rev. C **61**, 024901 (1999).