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Search for η' mesic nuclei by missing-mass spectroscopy of the ^{12}C(p,d) reaction

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Abstract. We performed a missing-mass spectroscopy experiment of the ^{12}C(p,d) reaction at 2.5 GeV proton energy in order to search for η' mesic nuclei. An excitation-energy spectrum of ^{11}C was obtained around the η' production threshold. As no significant peak structure was observed in the spectrum, upper limits of the formation cross section of η' mesic nuclei have been determined. Preliminary results of the experiment as well as future prospects are given.

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1 Introduction

The η' meson has a mass of 958 MeV/c^2, which is especially large compared with the other pseudoscalar mesons such as π, K, and η. This is theoretically understood as a consequence of the $U_A(1)$ anomaly, whose contribution to the η' mass is present under spontaneous and/or explicit chiral symmetry breaking in the low-energy region of QCD [1, 2]. In the nuclear medium, where chiral symmetry is partially restored, the mass of the η' meson may be reduced. Such a mass reduction would induce an attractive η'-nucleus interaction, and thus existence of η' meson-nucleus bound states (η' mesic nuclei) is theoretically suggested [3–5].

So far, in-medium properties of the η' meson are barely known. Theoretically, mass reductions of the η' meson at normal nuclear density have been predicted by various model calculations [5–8], but their results range from 37 MeV/c^2 to 150 MeV/c^2. From the experimental side, the CBELSA/TAPS collaboration measured η' meson photo-production off carbon nuclei, and indicated the real part of the η'-nucleus potential of $-(37 \pm 10 \pm 10)$ MeV with the imaginary part of $-(10 \pm 2.5)$ MeV at normal nuclear matter density [9, 10]. Such a small imaginary part implies possibility of experimentally observing η' meson-nucleus bound states as distinct narrow structures.

We designed an inclusive measurement of the ^{12}C(p, d) reaction to search for η' mesic nuclei, which can provide a unique opportunity to directly study in-medium properties of the η' meson [11]. We adopted the proton incident energy of 2.5 GeV to populate η' mesic states coupled with neutron hole states via the ^{12}C$(p, d)\eta' \otimes ^{11}$C reaction. The missing mass of the reaction is then obtained by measuring the momentum of the ejected deuteron. A measurement with good statistics is required, because a large amount of background events due to quasi-free multi-pion production (p+$N \rightarrow d$+π's) are expected in the inclusive spectrum. In the first experiment reported in this article, we aimed at achieving a high statistical sensitivity with a relative error size of $\sim 1\%$ in the spectrum to overcome the expected small signal-to-noise ratio.

2 Experiment

We performed a missing-mass spectroscopy experiment of the ^{12}C(p, d) reaction at GSI, Darmstadt in 2014. A 2.5 GeV proton beam extracted from the synchrotron (SIS-18) impinged onto a 4 g/cm^2-thick carbon target. Deuterons emitted at 0° in the ^{12}C(p, d) reaction were momentum-analyzed by the fragment separator (FRS) [12] used as a high-resolution spectrometer with an experimental setup shown in Fig. 1. We adopted a new ion optics mode which has an achromatic focal plane at F2 and a dispersive focal plane at F4 with a designed dispersion of ~ 3.6 cm/%. Two sets of multi-wire drift chambers (MWDCs) installed at F4 were used to measure the deuteron tracks. Data in the momentum range from 2.77 GeV/c to 2.93 GeV/c were accumulated by scaling the whole magnetic fields in the FRS by factors between 0.980 and 1.020.

Particle identification was provided by a time-of-flight between the two focal planes measured with plastic scintillation counters (SC2H, 2V, 41, and 42). In this experiment, a major experimental background particles at the downstream focal planes were protons emitted by the inelastic (p, p') reaction. Since the background protons have higher velocities ($\beta_p \sim 0.95$) than those of the signal deuterons ($\beta_d \sim 0.84$), they were clearly distinguished by a DAQ trigger based on the time-of-flight between F2 and F4. Furthermore, by analyzing recorded shapes of the signals of the scintillation counters, accidental multi-proton events were also rejected in the analysis. As a result, a contamination of the background protons in the spectrum was reduced to a negligible level with a fraction of $\sim 10^{-4}$ of the deuteron events.

The calibration of the spectrometer was carried out by measuring the D$(p, d)p$ elastic scattering using a 1.6 GeV proton beam and a CD_2 target. Monochromatic deuterons with the momentum of

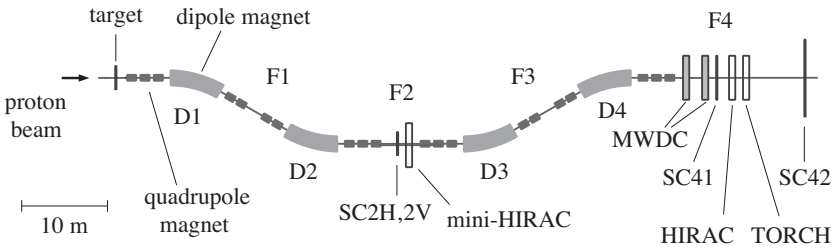

Figure 1. A schematic view of the experimental setup at the FRS. MWDCs were installed at the dispersive focal plane F4 to measure the deuteron tracks. Scintillation counters (SC2H, 2V, 41, and 42) were used for time-of-flight measurements. Čerenkov detectors (mini-HIRAC, HIRAC and TORCH) were used to tune a DAQ trigger condition.

2.8 GeV/c are emitted in this reaction, which is at the middle of the momentum range in the main measurements. By measuring these deuterons with various central momenta of the FRS, we confirmed the proper functionality of the spectrometer system, and calibrated the ion-optical parameters. Such measurements were repeated every $\sim$ 8 hours, and we monitored the stability of the whole system.

3 Preliminary results

The excitation-energy spectrum of ^{11}C was successfully obtained from -91 MeV to $+34$ MeV with respect to the η' emission threshold, as presented in Ref. [13]. In the spectrum, a high statistical sensitivity with a relative error of $< 1\%$ was achieved owing to the high-intensity proton beam and the thick carbon target. The experimental energy resolution was evaluated to be 2.5 MeV (σ), which is sufficiently small compared with expected widths of η' mesic nuclei.

Since no peak structure corresponding to η' mesic nuclei was observed in the excitation-energy spectrum, we determined upper limits of the formation cross sections of η' mesic nuclei. We tested a Voigtian peak, a Lorentzian peak folded by a Gaussian resolution, for each assumed energy and width of the state by a statistical method. The obtained upper limits near the η' emission threshold are about 0.1–0.2 μb/sr for the assumed Lorentzian width of Γ = 5 MeV, 0.2–0.4 μb/sr for Γ = 10 MeV, and 0.3–0.6 μb/sr for Γ = 15 MeV at 95% confidence level [13]. These upper limits are as small as theoretically-expected cross sections in case of deep η'-nucleus potential of the order of 100 MeV [4]. Furthermore, the obtained spectrum was also directly compared with the theoretically-calculated spectra to discuss a constraint for the η'-nucleus potential parameters [13].

4 Summary and future outlook

We performed the inclusive measurement of the ^{12}C(p, d) reaction at the proton energy of 2.5 GeV to search for η' meson bound states in carbon nuclei. The excitation-energy spectrum of ^{11}C was successfully obtained around the η' production threshold with the high statistical sensitivity and the sufficiently small energy resolution. In the spectrum, no significant peak structure corresponding to η' mesic bound states was observed. Thus, upper limits of the formation cross section of η' mesic states were determined. The experimental spectrum was also compared with theoretically calculated formation spectra to set a constraint on the η'-nucleus potential.

In the future, further experiments to search for η' mesic nuclei are necessary toward a direct study of in-medium properties of the η' meson. In order to achieve an even higher experimental sensitivity, we plan a semi-exclusive measurement of the ^{12}C(p, dp) reaction at GSI/FAIR [14]. In this experiment, while ejected deuterons are measured by a forward spectrometer such as FRS/Super-FRS, protons emitted in the decay of the η' mesic nuclei are identified around the reaction target. Tagging such protons is expected to suppress the background processes dominating in the present inclusive spectrum. R&D for the proton tagging system is in progress.

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