η' mesic nucleus spectroscopy with (p, d) reaction at GSI

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We have performed a spectroscopic experiment using the $^{12}C(p, d)$ reaction at 2.5 GeV incident energy to search for η' mesic nuclei for the first time. A missing-mass spectrum of the reaction was obtained around the η' emission threshold using the fragment separator FRS at GSI. An overview of the experiment including the status of the analysis is given.

1 Introduction

One feature of the η' meson is its large mass compared with other pseudoscalar mesons. This is theoretically understood as a consequence of the $U_A(1)$ anomaly, which contributes to the η' mass only with spontaneous and/or explicit breaking of chiral symmetry in the low-energy region of QCD [1, 2]. In the nuclear medium, in which chiral symmetry is partially restored, the mass of the η' meson can be reduced. Such a mass reduction induces an attraction between an η' and a nucleus, and η' meson-nucleus bound states (η' mesic nuclei) may exist [3, 4, 5].

So far, there are some theoretical and experimental studies for the η' meson in the nuclear medium. For example, in Nambu–Jona-Lasinio model calculations, around 150 MeV mass reduction is predicted at normal nuclear density [3, 6]. Experimentally, the CBELSA/TAPS collaboration claimed an attractive potential of about -37 MeV and an absorption width of $15-25$ MeV at nuclear matter density for an average η' momentum of 1050 MeV/c [7]. This small width implies that the decay width of η' mesic nuclei can be small as well.

In order to search for η' mesic nuclei and study in-medium properties of the η' meson, we performed an inclusive measurement of the ^{12}C(p, d) reaction for the first time in August 2014 [8]. A proton beam with kinetic energy of 2.5 GeV was used potentially to produce η' mesic states in ^{11}C nuclei, and the missing-mass for the reaction was measured by analyzing the momentum of the ejectile deuteron. In such an inclusive measurement, the signal-to-noise ratio is expected to be very small due to other background processes such as multi-pion production ($p + N \to d + \pi$'s). Thus a measurement with good statistics is required. Our simulation shows that observation of peak structures in an inclusive spectrum is feasible with the experimental conditions prevailing at the Fragment Separator (FRS) of GSI [9], if the mass reduction of the η' meson at normal nuclear density is as large as 150 MeV and the in-medium width is around 20 MeV [8].

2 Experiment

2.1 Experimental setup

Figure 1 shows the detector setup in the initial experiment carried out at the FRS. A 2.5 GeV proton beam with an intensity of the order of 10^{10} per a 4-second spill accelerated in SIS-18 synchrotron impinged onto a 4 g/cm^2 thick carbon target, and the ejectile deuterons were momentum-analyzed by the FRS used as a spectrometer. The tracks of the deuterons were measured by two sets of multi-wire drift chambers (MWDC's) at a dispersive focal plane (S4) with the dispersion of 3.6 cm/% to derive their momenta. The overall missing-mass resolution is expected to be about $\sigma \sim 1.6$ MeV/c^2, which is dominated by the straggling of the energy loss in the target. This is much smaller than the expected decay width of η' mesic nuclei and is sufficient for the measurement.

With this setup, a large amount of protons produced by the (p, p') inelastic scattering reach the S4 focal plane as a background. Thus, particle identification is necessary based on the velocity difference between the signal deuterons ($\beta_d \sim 0.83$) and the background protons ($\beta_p \sim 0.95$). Plastic scintillators (SC2H, SC2V, SC41, and SC42) were installed at the S2 and S4 areas for time-of-flight (TOF) measurements. Moreover, high-refractive-index aerogel Čerenkov detectors (HIRAC and mini-HIRAC) with silica aerogel radiators of a refractive index of $1.17-1.18$ [10] and a total-reflection Čerenkov detector (TORCH) with an Acrylite radiator were placed for further rejection of the background protons.

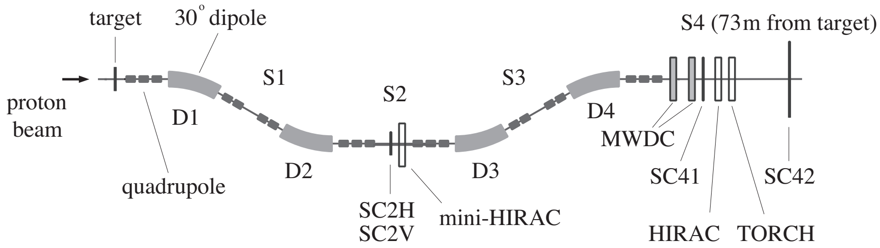

Figure 1: A schematic view of the experimental setup at the FRS. See the text for details.

2.2 Particle identification

A measured TOF spectrum between S2 and S4 with an unbiased trigger is shown in Figure 2. The smaller peak on the right side corresponds to the signal deuterons, and the higher peak on the left side is the background protons. The TOF difference between these two peaks is about 20 ns, which is consistent with our calculation. The ratio of the deuterons to the protons was about 1 to 200, and the total particle rate at the S4 focal plane was about 8×10^5/spill.

In the production measurements, we used a hardware trigger based on the S2-S4 TOF to reject the background protons and reduce the acquisition rate to the order of 10^3/s. Figure 3 shows the S2-S4 TOF and the TOF between the two scintillators at S4 (SC41-SC42) under this trigger condition. The proton peak seen in Figure 2 is rejected without influencing the signal deuterons. In Figure 3, accidental multi-proton events are still visible, whose amount is about the same as that of the signal deuterons. These can be rejected in the offline analysis by the TOF between the two S4 scintillators as shown in Figure 3, a waveform analysis of the S2 scintillator signals, and an analysis of the three Čerenkov detectors.

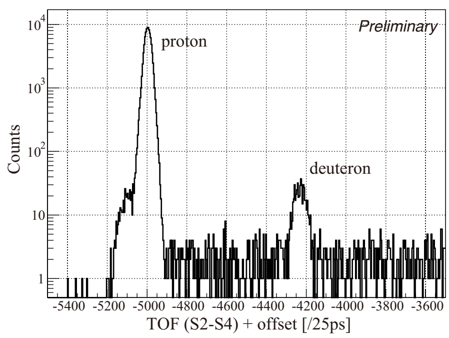

Figure 2: A measured TOF histogram between S2 and S4 by SC2H and SC41 with an unbiased trigger.

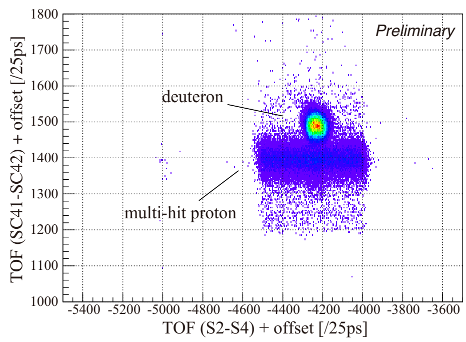

Figure 3: Measured TOF between S2 and S4 by SC2H and SC41 and TOF between two scintillators (SC41-SC42) at S4 with the TOF(S2-S4) trigger.

2.3 Momentum calibration

The momentum calibration was carried out by measuring the $d(p,d)p$ backward elastic scattering using a 1.6 GeV proton beam and a CD_2 target. In this reaction, monochromatic deuterons with the momentum of 2.8 GeV/c are emitted, which is at the middle of the momentum range in the production measurement. By measuring these deuterons at the S4 focal plane, the proper functionality of the whole system was confirmed and the ion-optical properties of the spectrometer were obtained.

2.4 Summary of measurements

We measured the ^{12}C(p,d) reaction with a 2.5 GeV proton beam for about 5 days. The excitation energy from roughly -90 MeV to $+40$ MeV from the η' emission threshold was investigated by measurements with several scaling factors for the FRS magnetic fields from 0.98 to 1.02. High statistical significance was achieved by measuring about (5–10)$\times 10^6$ deuterons for each setting.

As a reference, the $d(p,d)$ reaction was also measured in the same momentum range of the deuterons using a 2.5 GeV proton beam and a CD_2 target. In this measurement, peak structures related to η' mesic states are not expected. Thus, it provides information for understanding the background processes in this inclusive measurement.

3 Summary and future prospects

We have performed an inclusive measurement of the ^{12}C(p,d) reaction with a 2.5 GeV proton beam to search for η' mesic nuclei for the first time. A missing-mass spectrum of the ^{12}C(p,d) reaction was measured around the η' emission threshold with the expected spectral resolution of $\sigma \sim$1.6 MeV/c^2. The analysis of the spectrum is now in progress.

For FAIR, we are planning a semi-exclusive measurement of the (p,dp) reaction as well as an inclusive measurement of the (p,d) reaction with better statistics. The R&D is on-going.

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