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Search for η' -mesic nuclei using (p,d) reaction with FRS/Super-FRS at GSI/FAIR

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Abstract. We plan a semi-exclusive measurement of the $^{12}\text{C}(p,dp)$ reaction to search for η' -mesic nuclei, aiming at investigating in-medium properties of the η' -meson. We employ a 2.5 GeV proton beam impinging on a carbon target to produce η' -mesic ^{11}C nuclei via the $^{12}\text{C}(p,d)\eta' \otimes ^{11}\text{C}$ reaction. Using coincidence measurements of the forward going deuterons, important for missing-mass spectroscopy, and decay protons emitted from the η' -mesic nuclei



for event selection will provide a high experimental sensitivity to observe η' -mesic nuclei. We will perform the measurements by combining the WASA detector system with the fragment separator FRS at GSI and also with the Super-FRS at FAIR in the future. The plan of the experiments and the present status are reported.

1. Introduction

The especially large mass of the η' meson compared with the other pseudoscalar mesons (π , K , η) is theoretically understood by an interplay between $U_A(1)$ anomaly and chiral-symmetry breaking in QCD [1, 2]. In the nuclear medium, the mass of the η' meson is expected to be reduced due to partial restoration of chiral symmetry [1, 3, 4, 5, 6]. The mass reduction then leads to an attractive η' -nucleus potential, and the possible existence of η' meson-nucleus bound states (η' -mesic nuclei) is theoretically suggested [7, 8]. Such bound states, if observed, can serve as a unique testing ground for the experimental investigation of in-medium properties of the η' meson.

Information on the η' -nucleus potential is so far limited. Various theoretical models [3, 4, 5, 6, 9] are predicting η' mass reductions in the nuclear medium corresponding to the real part of the potential in a range of $-(37\text{--}150)$ MeV. On the experimental side, the CBELSA/TAPS collaboration deduced the real part of the η' -nucleus potential at the nuclear center to be $-[39 \pm 7(\text{stat}) \pm 15(\text{syst})]$ MeV [10, 11] and the imaginary part to be $-[13 \pm 3(\text{stat}) \pm 3(\text{syst})]$ MeV [12, 13] by measuring η' photo-productions off nuclear targets. Another available experimental information is the η' -proton scattering length, $\text{Re}(a_{\eta'p}) = 0 \pm 4.3$ fm and $\text{Im}(a_{\eta'p}) = 0.37^{+0.40}_{-0.16}$ fm, evaluated by the COSY-11 collaboration from measurements of the $pp \rightarrow pp\eta'$ reaction close to its threshold [14]. This indicates a potential depth smaller than 38 MeV within the low-density approximation.

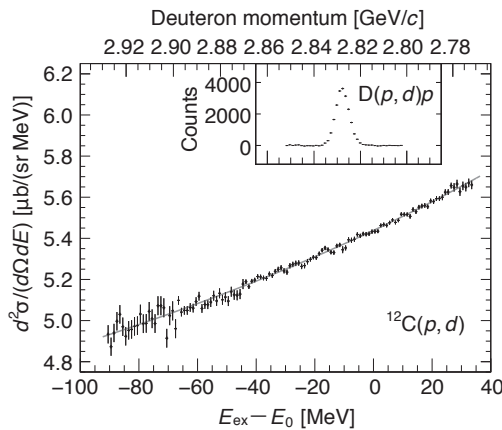


Figure 1. Excitation-energy of ^{11}C E_{ex} relative to the η' -production threshold E_0 measured in the $^{12}\text{C}(p, d)$ reaction at 2.5 GeV [16]. The inset shows a spectrum of the deuteron momentum obtained in the calibration $D(p, d)p$ reaction. See Ref. [16] for details.

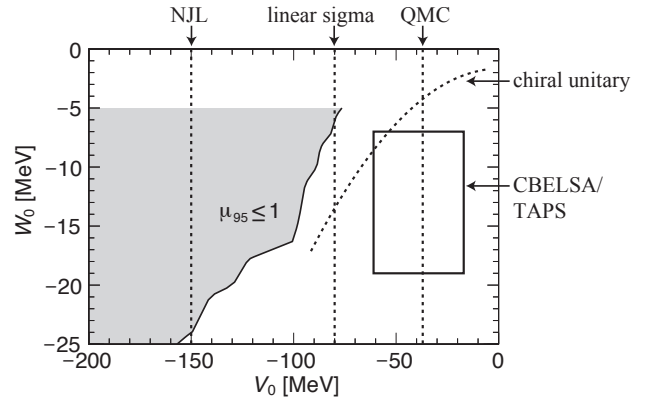


Figure 2. Constraint on the η' -nucleus potential ($V_0 + iW_0$) at the center of the nucleus deduced from the first experiment. The region with $\mu_{95} \leq 1$ is excluded by this analysis. Theoretical predictions [3, 4, 5, 6, 9] and indications from the CBELSA/TAPS experiment [10, 11, 12, 13] are displayed together. This figure is taken from Ref. [17].

In 2014, we performed a first experiment to search for η' -mesic nuclei by means of missing-

mass spectroscopy of the $^{12}\text{C}(p,d)$ reaction near the η' -meson production threshold [15, 16, 17]. A carbon target was irradiated with a 2.5 GeV proton beam from the SIS-18 synchrotron at GSI to produce η' -mesic nuclei via the $^{12}\text{C}(p,d)\eta' \otimes ^{11}\text{C}$ reaction. The momenta of the emitted deuterons were measured with the fragment separator (FRS) [18] used as a high-resolution spectrometer. The obtained excitation-energy spectrum of ^{11}C is shown in Fig. 1 [16, 17]. No clear peak structure of bound states was observed in spite of the achieved high statistical sensitivity. Thus, we determined upper limits for the formation cross section of η' -mesic nuclei to be ~ 20 nb/(sr MeV) at the threshold. Furthermore, we deduced a constraint on the η' -nucleus potential by comparison with theoretical calculations of the formation cross section [8]. As shown in Fig. 2, a large real-part potential $V_0 \sim -150$ MeV is excluded in this analysis, while for smaller V_0 the experimental sensitivity was insufficient to observe peak structures.

2. Semi-exclusive measurement of the $^{12}\text{C}(p,dp)$ reaction with FRS/Super-FRS at GSI/FAIR

In order to extend the experimental sensitivity towards a region of smaller real-part potentials, we propose a semi-exclusive measurement of the $^{12}\text{C}(p,dp)$ reaction [19]. In the first experiment of the $^{12}\text{C}(p,d)$ reaction, the obtained excitation spectrum (Fig. 1) was dominated by the continuous background from quasi-free meson production ($p + N \rightarrow d + X$, where $X = 2\pi, 3\pi, 4\pi, \omega$). In the next semi-exclusive measurement, we additionally detect protons from the decay of η' -mesic nuclei. Figure 3 displays simulated kinetic-energy distribution of protons emitted from three expected major decay modes of η' -mesic nuclei [20] by assuming the Fermi motion of nucleons in the nucleus. In particular, protons from the two-nucleon absorption process have relatively high energies of about 300–600 MeV. A simulation with an intra-nuclear cascade model [21] has shown that tagging such protons can provide an improvement factor of ~ 100 in the signal-to-background ratio of the spectrum [22].

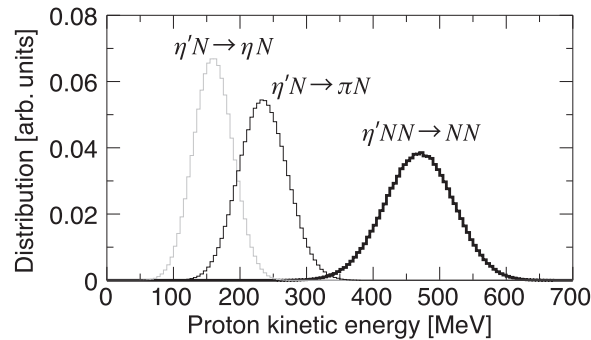


Figure 3. Simulated kinetic-energy distribution of protons from the decay of η' -mesic nuclei. One-nucleon absorption processes ($\eta'N \rightarrow \eta N$, $\eta'N \rightarrow \pi N$) and two-nucleon absorption process ($\eta'NN \rightarrow NN$) are considered. The integral of each distribution is normalized to 1. This figure is taken from Ref. [17].

We plan to perform the proposed semi-exclusive measurement with the FRS at GSI and in the future with the Super-FRS [23] at FAIR. The spectrometers FRS and Super-FRS will be used to measure the momentum of the forward going deuteron for missing-mass spectroscopy. In addition, a large-acceptance detector system will be installed surrounding the reaction target to identify the decay protons and tag the events associated with the formation of η' -mesic nuclei.

Figure 4 shows the proposed experimental setup with the WASA central detector system [24, 25] combined with the FRS. A 2.5 GeV proton impinges on a carbon target placed in the

WASA system at F2. The forward going deuteron emitted in the (p,d) reaction is analyzed by the second half of the FRS (F2–F4) at a high momentum resolving power of $\sim 4 \times 10^3$. Multi-wire drift chambers (MWDCs) at F4 are used to measure the trajectories of the particles. Deuterons are identified with the measured time-of-flight between the plastic scintillators installed at F3 and F4 and by an aerogel Cherenkov detector (AC) at F4. The WASA detector system (Fig. 5), consisting of a super-conducting solenoid magnet, plastic scintillator barrel (PSB), and mini drift chamber (MDC), identifies the decay protons emitted from η' -mesic nuclei.

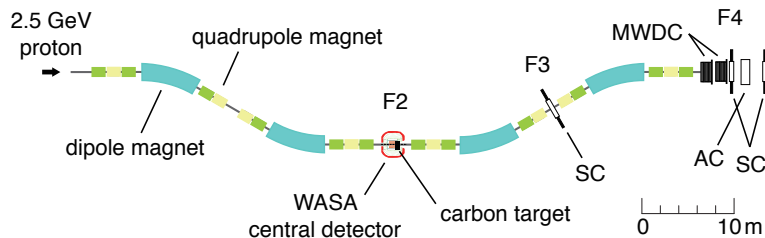


Figure 4. Proposed experimental setup with the WASA central detector and the FRS spectrometer at GSI. A 2.5 GeV proton beam impinges on a carbon target at F2. Deuterons emitted in the (p,d) reaction are momentum-analyzed in the F2–F4 section of FRS. Decay particles from η' -mesic nuclei are detected by the WASA detector at F2.

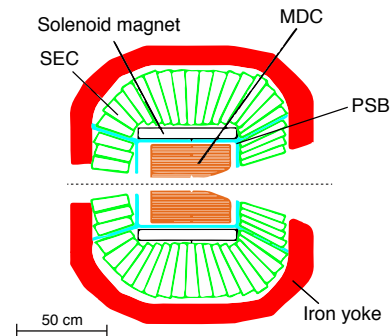


Figure 5. A schematic view of the WASA central detector [24, 25].

3. Status of preparations for the experiment with WASA and FRS

Presently, we are preparing the realization of the new experimental setup with the WASA detector system combined with the FRS. The WASA detector system, which had been used at the cooler synchrotron COSY at Forschungszentrum Jülich, has been transported to GSI in 2019. The detector components and the super-conducting solenoid magnet are being tested at GSI and will be integrated into the F2 area of the FRS.

Among the detector components, the PSB will be upgraded by using multi-pixel photon counters (MPPCs) in order to improve the time resolution to $\sigma \sim 100$ ps. The time resolution of the original PSB was limited by the fact that scintillation photons were detected only at one end of the plastic bar. Therefore, we install photon detectors at both ends of the plastic, and we adopt MPPCs for this purpose, because at least one detector has to be placed in the magnetic field due to a geometrical constraint. So far, we have developed a prototype of this new PSB and tested it with a proton beam at COSY. Figure 6 shows a typical time-of-flight (TOF) spectrum between two identical PSB prototypes placed directly behind each other. The TOF resolution of $\sigma_{\text{TOF}} \sim 90$ ps has been achieved in a preliminary analysis, which corresponds to the time resolution of the single PSB $\sigma_{\text{PSB}} \sim 65$ ps [26].

The MDC detector has been reassembled at GSI and tested with cosmic-ray particles. An example of a reconstructed trajectory projected onto the XY-plane, perpendicular to the Z direction of the beam pipe, is displayed in Fig. 7. Hit information in the axial layers parallel to the Z axis is shown in red, and that in the skewed layers by positive (negative) angles is shown in blue (green). The centers and radii of the circles represent positions of the wires with hits and the analyzed drift lengths, respectively. The tests with the cosmic rays have demonstrated that the MDC detector is properly functioning and has a good performance after the transportation to GSI.

Preparations and tests of the other components are also ongoing. In 2020, we plan to integrate the WASA system into the FRS and aim at starting the physics runs in 2021.

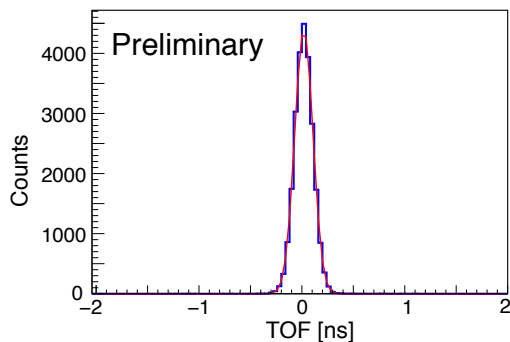


Figure 6. A preliminary time-of-flight spectrum between two new PSB prototype detectors obtained with a proton beam at 2.5 GeV/c.

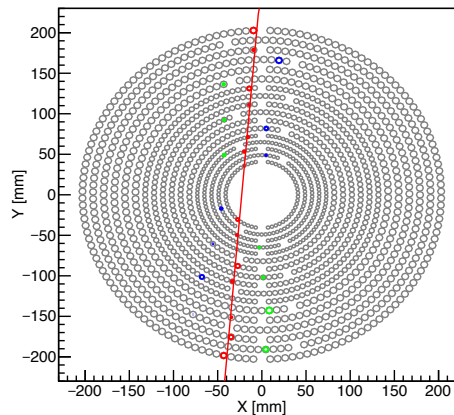


Figure 7. A typical event display of MDC tested with cosmic rays. See text for details.

4. Summary

We propose a semi-exclusive measurement of the $^{12}\text{C}(p,dp)$ reaction to search for η' -mesic nuclei. Simultaneous measurements of the deuteron for missing-mass spectroscopy and the decay protons from η' -mesic nuclei for event selection will lead to a high experimental sensitivity. We plan to conduct the experiment by using the WASA central detector combined with the fragment separator FRS or Super-FRS in the future. Preparations and developments for this new experimental setup are in progress. The first experiment is expected to start in 2021.

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