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Search for η'-mesic nuclei in ^{12}C(p, dp) reaction with the WASA detector at GSI-FRS

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Summary. — We conducted an experimental search for η'-mesic nuclei, bound systems of an η' meson and a nucleus, in $^{12}\mathrm{C}(p, dp)$ reactions. We measured the missing mass in the (p, d) reaction to obtain the mass spectrum of the reaction product near the η' emission threshold. Forward-emitted deuterons were momentum-analyzed in the FRS of GSI. We installed a nearly 4π detector WASA near the $^{12}\mathrm{C}$ target to effectively select formation and decay of the η'-mesic nuclei. We are presently finalizing the analysis.

1. – Introduction

The mass of the η' meson is much larger than that of the other members of the lowest pseudoscalar nonet. Theoretically, the nine mesons are mass-degenerate as manifestation of chiral symmetry [1,2], while the masses reflect the underlying symmetry of the vacuum. The eight members except for the η' are "massless" Nambu-Goldstone bosons, which are produced in the breakdown of chiral symmetry. The large η' mass is a key to achieve a comprehensive understanding of the non-trivial structure of the QCD vacuum and the mechanism for the generation of the hadron masses.

According to theories, the peculiarly large mass of η' originates in the interplay between the axial $U(1)$ quantum anomaly and the chiral symmetry breakdown of the QCD vacuum [3, 4]. Thus the mass is reduced when the chiral symmetry is restored. We aim at a measurement of the mass modification in experimental spectroscopy of η'-mesic nuclei. In high-density conditions, chiral symmetry is partially restored in the nucleus. Recently, high-precision spectroscopy of pionic atoms provided quantitative information on the chiral order parameter $\langle\bar{q}q\rangle$ at nuclear density $\rho = 0.098\ \mathrm{fm}^{-3}$. The evaluated $\langle\bar{q}q\rangle$ is reduced to $77 \pm 2\%$ of that in vacuum, representing a partial restoration of chiral symmetry in nuclear matter [5, 6].

The reduction of the mass is represented by the attractive real part of the η'-nucleus potential, which is naively assumed to have a form of $U(r) = (V_0 + iW_0)\,\rho(r)/\rho(0)$, where $\rho(r)$ denotes the nuclear density and r is the distance from the center of the nucleus. The predicted mass reduction depends on theoretical models ranging from $\Delta m = 37$ to $150\,\mathrm{MeV}/c^2$. Such a large mass reduction compared with its rest mass of $958\,\mathrm{MeV}/c^2$ presumes the existence of an attractive potential and hence the existence of the η'-mesic nuclei. Figure 1 displays the η'-nucleus interaction represented on a plane of real ($V_0 \approx -\Delta m$) and imaginary (W_0) potential depths at the center of the nucleus. Theoretical results of different approaches are shown with solid lines for a quark meson coupling model [7] (shown as QMC), a linear sigma model [8] (linear σ), a Nambu–Jona-Lasinio model [9, 10] (NJL) and a chiral unitary model [2]. The differences in theoretical predictions reflect the theoretical uncertainties. Experimentally, derived data are shown for the production and transmission measurements in CB-ELSA/TAPS experiment [11, 12] and on η'-nucleon scattering lengths measured at COSY-11 [13].

Expected spectra of the $^{12}\mathrm{C}(p, d)$ reactions are theoretically calculated for differently assumed η'-nucleus interactions in ref. [14]. In a previous experiment, GSI-S437, we measured the missing-mass spectrum of the $^{12}\mathrm{C}(p, d)$ reaction [15, 16]. We achieved very high statistics but did not observe any significant structure near the η'-production threshold

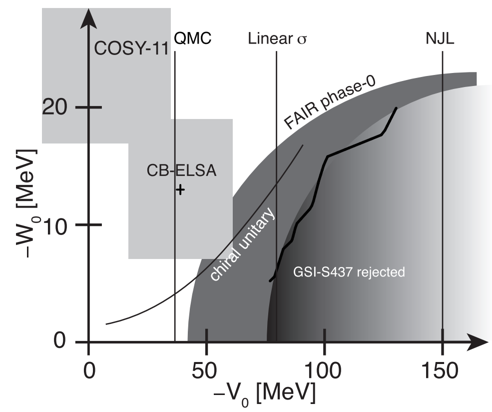

Fig. 1. – Present knowledge of η'-nucleus interaction. In FAIR phase-0 we aim at η'-mesic nuclei search in the region covered by the sector indicated. The shaded region labeled with "GSI-S437 rejected" is excluded by the GSI-S437 experiment [17] where an inclusive spectrum of ^{12}C(p, d) reaction was measured [15] on an assumption of the elementary reaction cross-section. Transparency and near-threshold production cross-section and momentum measurements at CB-ELSA deduce $-V_0 = 39 \pm 7(stat) \pm 15(syst)\,$MeV and $-W_0 = 13 \pm 3(stat) \pm 3(syst)\,$MeV as indicated [11, 12]. Measurement of $\eta' N$ scattering length in COSY-11 [13] infers the region as indicated. Theoretical results of different approaches are presented for a quark meson coupling model [7] (shown as QMC), a linear sigma model [8] (linear σ), a Nambu–Jona-Lasinio model [9, 10] (NJL) and a chiral unitary model [2].

because of dominating background events. To reduce the background, a new experiment has been performed measuring the decay products of the η'-mesic states in coincidence with the forward-going deuteron. There are several candidate channels in the decay, namely, $\eta' N \to \pi N$, $\eta' N \to \eta N$, $\eta' N \to K\Lambda$, and $\eta' NN \to NN$. Among them, the two-nucleon absorption channel, $\eta' NN \to NN$, is interesting. This channel does not emit light particles, hence the kinetic energy of the emitted proton is approximately half of the mass of the η', which is much higher than that of protons in other channels. Therefore, we can effectively select the formation and decay of the η'-mesic nuclei by tagging the high-energy protons. This naive expectation is endorsed by a nuclear transport simulation, which suggests an improvement of the SB ratio by a factor of about 100. By performing the semi-exclusive measurement and tagging the decay of the η'-mesic nuclei, we aim to extend the exploratory region to that indicated as FAIR phase-0 in fig. 1 covering the predicted curve of the chiral unitary model.

2. – Experiment and analysis

We conducted an experimental search for the η'-mesic nuclei in the ^{12}C(p, dp) reaction at GSI in 2022. We employed a proton beam with an incident energy of 2.5 GeV. The momentum transfer in the reaction is moderate: $q \sim 500\,\mathrm{MeV}/c$.

The experimental setup is schematically shown in fig. 2(a). As seen, the present experiment utilizes a totally new type of experimental setup in a combination of a nearly 4π detector and a forward high-resolution spectrometer. We made use of the S2–S4 section of the Fragment Separator (FRS) [18] as a spectrometer to momentum-analyze the forward deuteron in the (p, d) reactions to measure the missing mass of the reaction. We installed two sets of multi-wire drift chambers (MWDCs) with 8 detection layers

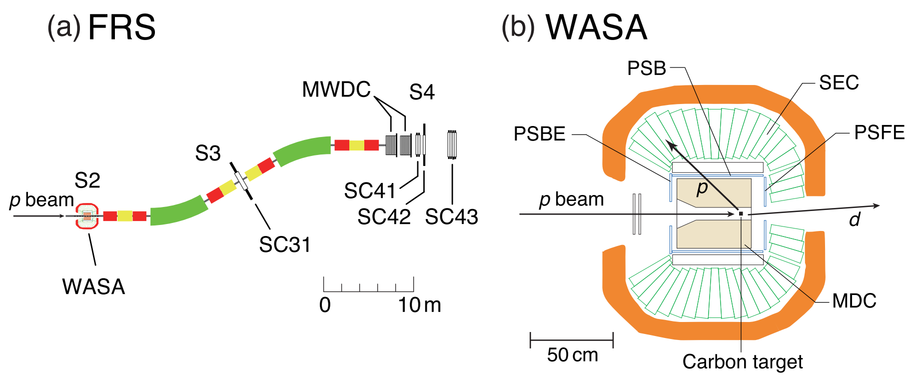

Fig. 2. – (a) A schematic view of the spectrometer FRS. We placed a carbon target at S2 and momentum-analyzed the emitted deuteron at S4, where we installed two sets of MWDCs and sets of scintillation counters. (b) A cross-section of the WASA central detector installed at S2.

at S4 to measure the d tracks. We employed dedicated ion optics to enhance the solid angle for detecting the deuteron to achieve $\sim$2 msr, which is much larger than in nominal settings, and momentum acceptance of $\pm 1.1\%$, which corresponds to an excitation energy acceptance of $\pm$ 25 MeV. The achieved S4 position resolution per layer was as good as 300–400 μm (σ). We installed sets of scintillation counters at S3 and S4 to measure the time of flight and the energy loss of particles to identify events with an emitted deuteron. The counting rate at S4 was $\sim$ 40 kHz, mainly due to protons, while the signal deuteron rate was $\sim$ 30 Hz. The DAQ trigger was generated by a coincidence based on time-of-flight difference of particles between S3 and S4 scintillation counters. We achieved background-free deuteron identification in the offline data analysis.

For the measurement of the decay particles of the η'-mesic nuclei, we installed a $\sim 4\pi$ acceptance detector WASA [19] at the central focal plane of FRS (S2). Detector configurations of WASA are schematically shown in fig. 2(b). WASA consists of a solenoid magnet with field strength of $\sim$ 1 T, a set of straw tube detectors for charged particle

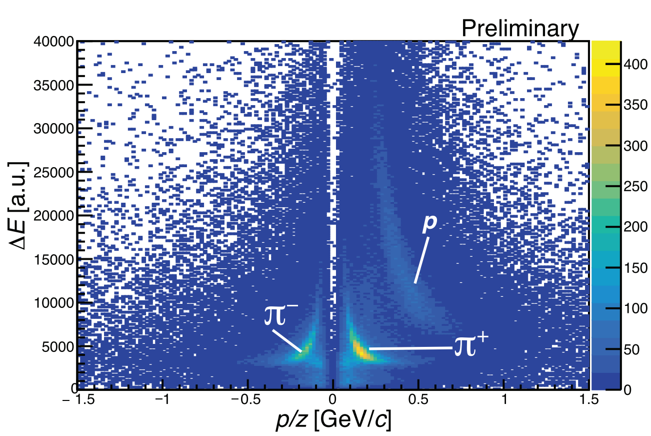

Fig. 3. – Typical particle identification performance of WASA. The abscissa is the momentum divided by the charge measured by the MDC. The ordinate is the energy loss measured in the plastic scintillation counters.

tracking (MDC) and arrays of plastic scintillation counters (PSB, PSFE, PSBE). The plastic scintillation counters were newly developed using MPPCs for the photon readout to improve the timing resolution [20]. Counting rates of WASA are estimated to be $\sim$20 MHz for a 2.5 GeV proton beam with flux 2.5×10^8 p/s incident on a carbon target with density 4 g/cm^2. We are still analyzing the data. The overall performance of WASA is demonstrated in fig. 3. Protons, π^+, and π^- are clearly separated as shown. In the near future, we will obtain the missing-mass spectrum of the ^{12}C(p, dp) near the η' emission threshold with various cut conditions for the semi-exclusive measurement. We have almost completed the analysis of the forward-emitted deuteron in the S2–S4 section of FRS and are finalizing the analysis of data recorded by the WASA central detector.

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