FIRST RESULTS ON THE EXPERIMENTAL SEARCH FOR η'-MESIC NUCLEI WITH THE ^{12}C(p,d) REACTION*

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We performed a missing-mass spectroscopy experiment of the $^{12}\mathrm{C}(p,d)$ reaction in order to search for η'-mesic nuclei. Excitation spectrum of $^{11}\mathrm{C}$ around the η'-meson production threshold was successfully obtained with a high-statistical sensitivity and sufficiently good energy resolution. Since no peak structure associated with the formation of η'-mesic nuclei was observed, we set constraints on the formation cross sections of η'-mesic states and on the η'–nucleus interaction.

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1. Introduction

The η' meson has a mass of 958 MeV/c^2, which is peculiarly large among the light pseudoscalar mesons. This is theoretically attributed to the $\mathrm{U_A}(1)$ anomaly in QCD with the spontaneous breaking of chiral symmetry [1, 2]. At finite nuclear density, chiral symmetry is expected to be partially restored [3–5], and the mass of the η' meson may be reduced. Theoretical calculations based on the Nambu–Jona-Lasinio model [6, 7], linear sigma model [8], and quark–meson coupling model [9] predict η' mass reductions of -150, -80, and -37 MeV at normal nuclear density, respectively. The mass reduction then induces an attractive η'–nucleus potential, which leads to a possible existence of η' meson–nucleus bound states (η'-mesic nuclei) [7, 10, 11].

Experimental information on the η'–nucleus interaction is still very limited. The CBELSA/TAPS Collaboration deduced an attractive η'–nucleus potential of $-39 \pm 7(\mathrm{stat.}) \pm 15(\mathrm{syst.})$ MeV at the nuclear center from η'-momentum distributions and excitation functions in η' photoproduction off nuclear targets [12, 13]. They also evaluated the imaginary part of the potential to be $-13 \pm 3(\mathrm{stat.}) \pm 3(\mathrm{syst.})$ MeV from measured transparency ratios [14, 15]. Such a small imaginary part relative to the real part suggests possibilities of experimentally observing η'-mesic nuclei as narrow peak structure. Another experimental information is the η'–proton scattering length of $\mathrm{Re}(a_{p\eta'}) = 0 \pm 0.43$ fm and $\mathrm{Im}(a_{p\eta'}) = 0.37^{+0.40}_{-0.16}$ fm [16] extracted from a measurement of the $pp \to pp\eta'$ reaction close to its threshold. This indicates a relatively weak attraction in the η'–nucleus system.

2. Experiment

In order to search for η'-mesic nuclei, we performed a missing-mass spectroscopy experiment of the $^{12}\mathrm{C}(p,d)$ reaction [17–19]. A 2.5 GeV proton beam extracted from the synchrotron SIS-18 at GSI impinged on a 4 g/cm^2-thick carbon target. The deuterons emitted at 0° in the $^{12}\mathrm{C}(p,d)$ reaction were momentum-analyzed with the fragment separator (FRS) [20] used as a high-resolution spectrometer.

The experimental setup is schematically shown in Fig. 1. We employed a special ion-optical mode of the FRS with a momentum-achromatic focus at F2 and a dispersive focus at F4. Multi-wire drift chambers (MWDCs) were installed at the F4 dispersive focal plane to reconstruct the deuteron tracks and thereby obtain their momenta. Scintillation counters (SC2H, SC2V, SC41, SC42) were used for time-of-flight measurements to distinguish the deuterons from background protons. Moreover, Čerenkov counters (AC, TORCH) were installed to crosscheck the identification of the deuterons.

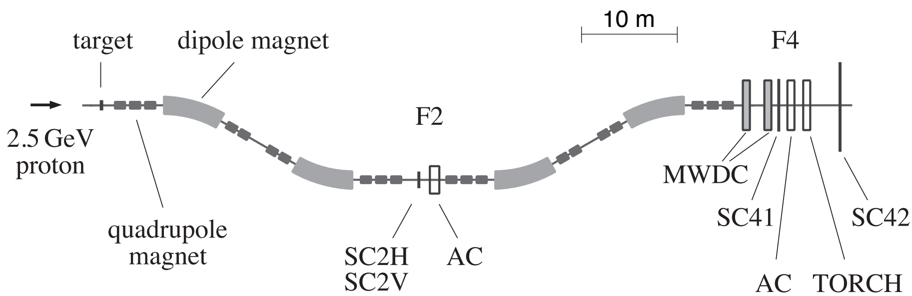

Fig. 1. A schematic view of the experimental setup with the FRS. A carbon target was irradiated with a 2.5 GeV proton beam. The momentum of the deuteron emitted in the (p, d) reaction was measured by two sets of multi-wire drift chamber (MWDC) at the F4 dispersive focal plane. Scintillation counters (SC2H, SC2V, SC41, SC42) were used for time-of-fight measurements. Čerenkov detectors (AC, TORCH) were installed for confirmation of particle identification.

Data of the ^{12}C(p, d) reaction were accumulated for about 70 hours with several settings of the central momentum of the FRS spectrometer. The excitation-energy region from -91 to $+34$ MeV relative to the η'-emission threshold was investigated. In addition, the proton–deuteron elastic scattering was measured by using a 1.6 GeV proton beam and a CD_2 target. Mono-energetic deuterons emitted at 0° in this reaction were used as a reference to calibrate the ion-optical response of the spectrometer.

3. Results

Obtained excitation-energy spectrum is presented in Fig. 2. The horizontal axis gives the ^{11}C excitation energy ($E_{\rm ex}$) relative to the η'-meson emission threshold ($E_0 = 957.78$ MeV). The spectrum shows a gradual increase from 4.9 to 5.7 μb/(sr × MeV), where the continuous component can be understood by quasi-free meson production processes $p + N \to d + X$ $(X = 2\pi, 3\pi, 4\pi, \omega)$ [17]. The experimental resolution was evaluated to be 2.5 MeV (σ) from the width of the D$(p, d)p$ peak in the calibration measurement, as shown in the inset. A very high statistical sensitivity with $\leq 1\%$ relative errors was achieved. However, no peak structure associated with the formation of the η'-mesic nuclei was observed.

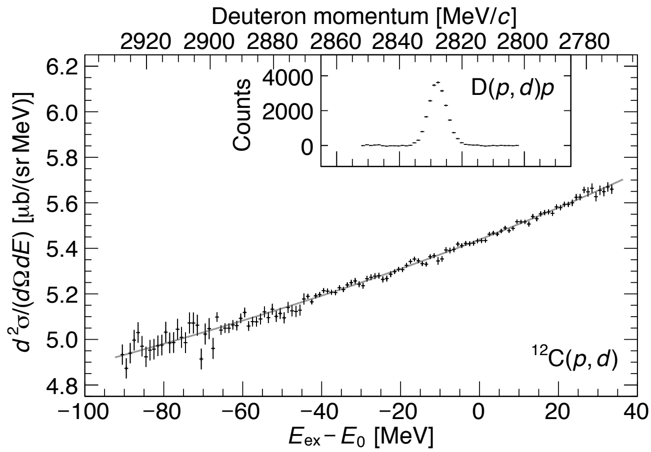

Fig. 2. Excitation spectrum of ^{11}C measured in the ^{12}C(p, d) reaction at 2.5 GeV. The horizontal axis is the ^{11}C excitation energy E_{ex} relative to the η'-meson production threshold $E_0 = 957.78$ MeV. The gray curve shows a fit with a third-order polynomial. The inset displays a momentum spectrum of the deuterons in the calibration D$(p, d)p$ reaction at 1.6 GeV. This figure is adopted from Ref. [18].

Since no peak structure was seen in the excitation-energy spectrum, we evaluated upper limits of the formation cross sections of the η'-mesic nuclei by statistically testing the existence of a Lorentzian-shaped peak at different peak positions and widths. Thus obtained upper limits near the η' emission threshold are 0.1–0.2 μb/sr for the assumed Lorentzian width of $\Gamma = 5$ MeV, 0.2–0.4 μb/sr for $\Gamma = 10$ MeV, and 0.3–0.6 μb/sr for $\Gamma = 15$ MeV at the 95% confidence level [18]. These limits are as small as theoretically predicted peak structures for a strongly attractive potential of the order of $V_0 \sim -150$ MeV [11].

Furthermore, the obtained spectrum was directly compared with the theoretically calculated spectra [11] for various strengths of the η'–nucleus potential in -200 MeV $\leq V_0 \leq -50$ MeV and -20 MeV $\leq W_0 \leq -5$ MeV. We introduced a scale parameter μ for the theoretical formation cross section, and evaluated upper limit of μ at 95% C.L. [18]. The resultant upper limit (μ_{95}) is shown in Fig. 3 as a contour plot on the real and imaginary potential strengths $(|V_0|, |W_0|)$ at nuclear saturation density. Here, we can exclude potential sets giving $\mu_{95} \leq 1$. Thus, a strongly attractive potential $|V_0| \sim 150$ MeV is excluded under the present comparison for the imaginary part of $|W_0| \sim$ 10 MeV [14, 15].

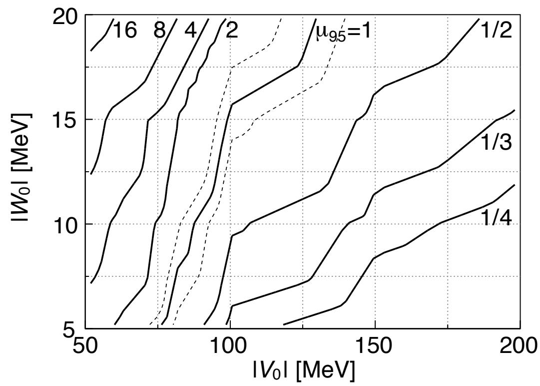

Fig. 3. The 95% C.L. upper limits (μ_{95}) on the scale parameter μ, introduced for the theoretically calculated formation spectra. The limits are given by the contours on the real and imaginary potential plane ($|V_0|, |W_0|$). The dashed curves indicate the systematic errors for the contour of $\mu_{95} = 1$. The potential region giving $\mu_{95} \leq 1$ can be excluded by the present analysis. This figure is adopted from Ref. [18].

4. Summary and future prospects

We measured the excitation spectrum of ^{11}C around the η'-meson production threshold to search for η'-mesic nuclei. Although high statistical sensitivity and sufficient energy resolution were achieved in the spectrum, no distinct structure due to the formation of the η'-mesic nuclei was observed. We determined upper limits on the formation cross sections of the η'-mesic states. A comparison with theoretically calculated formation spectra excluded strongly attractive η'–nucleus potentials.

In the near future, we will perform a semi-exclusive measurement of the ^{12}C(p, dp) reaction to improve the experimental sensitivity. One of the expected decay modes of the η'-mesic nuclei is a two-nucleon absorption process ($\eta' NN \rightarrow NN$) [21], where a high-energy proton with $T_p \sim 500$ MeV can be emitted. A coincidence measurement of the forward deuteron and the decay proton can drastically improve the signal-to-background ratio. Detailed consideration of the experimental setup is ongoing.

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