

Spectroscopy of η' -mesic nuclei with WASA at GSI/FAIR *

Y. K. TANAKA^a, S. BAGCHI^a, J. BENLLIURE^b, T. DICKEL^a,
V. DROZD^{a,c}, H. EKAWA^d, H. FUJIOKA^e, H. GEISSEL^{a,f},
F. GOLDENBAUM^g, C. GUO^h, E. HAETTNER^a, M. N. HARAKEY^{c,a},
R. S. HAYANOⁱ, Y. HE^j, S. HIRENZAKI^k, C. HORNUNG^f, Y. IGARASHI^l,
N. IKENO^m, K. ITAHASHI^d, M. IWASAKI^d, D. JIDO^e,
N. KALANTAR-NAYESTANAKI^c, R. KANUNGOⁿ, B. KINDLER^a,
R. KNÖBEL^{a,f}, D. KOSTYLEVA^a, N. KURZ^a, N. KUZMINCHUK^a, E. LIU^j,
B. LOMMEL^a, Y. MA^d, S. Y. MATSUMOTO^o, V. METAG^f, S. MINAMI^a,
P. MOSKAL^p, I. MUKHA^a, A. MUNEEM^d, T. NAGAE^o, H. NAGAIRO^k,
M. NAKAGAWA^d, H. J. ONG^q, H. OUTA^d, S. PIETRI^a, W. R. PLASS^a,
A. PROCHAZKA^a, S. PURUSHOTHAMAN^a, X. QIU^j, C. RAPPOLD^a,
J. RITMAN^g, J. L. RODRÍGUEZ-SÁNCHEZ^b, R. RUBER^r, O. RUNDEL^p,
T. R. SAITO^{a,d}, C. SCHEIDENBERGER^{a,f}, R. SEKIYA^o, V. SERDYUK^g,
H. SIMON^a, B. SITAR^s, M. SKURZOK^{p,t}, P. STRMEN^s, B. SUN^h,
B. SUN^j, I. SZARKA^s, M. TAKECHI^u, I. TANIHATA^{q,h}, S. TERASHIMA^h,
H. WEICK^a, A. YAMAMOTO^l, J. ZHAO^h
(η -PRiME/Super-FRS Experiment Collaboration)

^aGSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

^bUniversidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain

^cKVI-CART, University of Groningen, 9747 AA Groningen, the Netherlands

^dRIKEN, Wako, 351-0198 Saitama, Japan

^eTokyo Institute of Technology, 152-8550 Tokyo, Japan

^fUniversität Giessen, 35392 Giessen, Germany

^gForschungszentrum Jülich, 52425 Jülich, Germany

^hBeihang University, 100191 Beijing, China

ⁱThe University of Tokyo, 113-0033 Tokyo, Japan

^jLanzhou University, Lanzhou, 730000 Gansu, China

^kNara Women's University, 630-8506 Nara, Japan

^lKEK, Tsukuba, 305-0801 Ibaraki, Japan

^mTottori University, 680-8551 Tottori, Japan

ⁿSaint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada

^oKyoto University, 606-8502 Kyoto, Japan

^pJagiellonian University, 30-348 Kraków, Poland

^qRCNP, Osaka University, Ibaraki, 567-0047 Osaka, Japan

^rUppsala University, 75120 Uppsala, Sweden

^sComenius University Bratislava, 842 48 Bratislava, Slovakia

^tINFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy

^uNiigata University, 950-2181 Niigata, Japan

We plan to conduct an experimental search for η' -mesic nuclei in order to investigate in-medium properties of the η' meson. A 2.5 GeV proton beam is employed to produce η' -mesic ^{11}C nuclei with the $^{12}\text{C}(p,d)\eta'\otimes^{11}\text{C}$ reaction. Simultaneous measurements of the forward ejected deuterons and decay protons from η' -mesic nuclei will allow us to achieve high experimental sensitivity. The experiment will be performed at GSI by making full use of the fragment separator FRS and the WASA detector system. The plan of this proposed experiment is described.

PACS numbers: 13.60.Le, 14.40.Be, 25.40.Ve, 21.85.+d

1. Introduction

Possible existence of η' -meson nucleus bound states (η' -mesic nuclei) has recently attracted both theoretical and experimental interests, since such bound states reflect η' meson properties in finite nuclear density [1, 2]. The peculiarly large mass of the η' meson in vacuum is theoretically understood by an interplay between $U_A(1)$ anomaly and chiral symmetry breaking [3, 4]. Thus, the η' mass may be reduced in finite nuclear density due to partial restoration of chiral symmetry [3, 5, 6, 7, 8]. Such mass reduction would induce an attractive η' -nucleus potential, leading to a possible existence of η' -mesic nuclei [9, 10].

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 [11, 12, 13]. Although good statistical sensitivity and energy resolution were achieved, no significant peak structure due to the formation of the η' -mesic states was observed in the measured excitation spectra. We determined upper limits for the formation cross sections of η' -mesic nuclei and deduced a constraint on the η' -nucleus potential ($V_0 + iW_0$) at normal nuclear density, as shown by the gray area in Fig. 1 [12, 13]. A relatively large real potential ($V_0 \sim -150$ MeV) is excluded in the analysis of this first experiment, while the experimental sensitivity is still not sufficient to find peak structures in the case of smaller real potentials.

* Presented at the 3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics

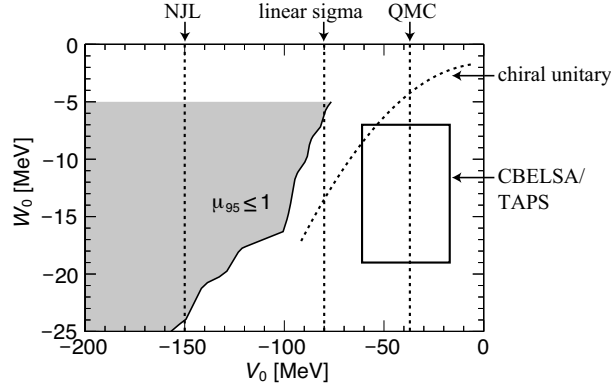


Fig. 1. Constraint on the η' -nucleus potential ($V_0 + iW_0$) at normal nuclear density obtained from the first experiment. This figure is taken from Ref. [13]. Theoretical predictions [5, 6, 7, 8, 14] and indications from the CBELSA/TAPS experiment [15, 16, 17, 18] are shown as well. See Ref. [13] for details.

2. Experiment with WASA at GSI/FAIR

2.1. Experimental Principle and Method

We propose a measurement of the $^{12}\text{C}(p,dp)$ reaction in order to search for η' -mesic nuclei with further increased experimental sensitivity [19]. We employ a 2.5 GeV proton beam to produce η' -mesic nuclei in the $^{12}\text{C}(p,d)\eta' \otimes ^{11}\text{C}$ reaction. The excitation energy of ^{11}C is obtained by precisely measuring the momentum of the ejectile deuteron. In addition, protons emitted from decay of the η' -mesic nuclei are identified to select events associated with the formation of η' -mesic nuclei. A large amount of physical background processes in the $^{12}\text{C}(p,d)$ reaction, such as quasi-free multi-pion production, are thus suppressed, leading to a better signal-to-background ratio of the excitation spectrum than that in the first inclusive measurement.

This experiment is feasible at GSI by combining the fragment separator (FRS) [20] and the WASA central detector system [21, 22]. FRS is a versatile high-resolution spectrometer, as shown in Fig. 2, and suitable for the measurement of the ejectile deuterons at 0° . The WASA central detector system, consisting of a superconducting solenoid magnet, a mini drift chamber, plastic scintillator barrel, and CsI electromagnetic calorimeter, covers nearly the full solid angle and is ideal for the detection of the decay particles.

Figure 2 shows a schematic view of the detailed experimental setup. A 2.5 GeV proton beam accelerated by the synchrotron SIS-18 is injected to a carbon target placed inside the WASA central detector at F2. Emitted deuterons in the $^{12}\text{C}(p,dp)$ reactions are momentum-analyzed by the F2-F4 section of FRS operated as a high-resolution spectrometer. Trajectories of

the particles are measured by multi-wire drift chambers (MWDCs), and deuterons are identified by time-of-flight measurements with plastic scintillators (SCs) and by an aerogel Cherenkov detector (AC). Protons emitted from the decay of η' -mesic nuclei are identified by the WASA central detector.

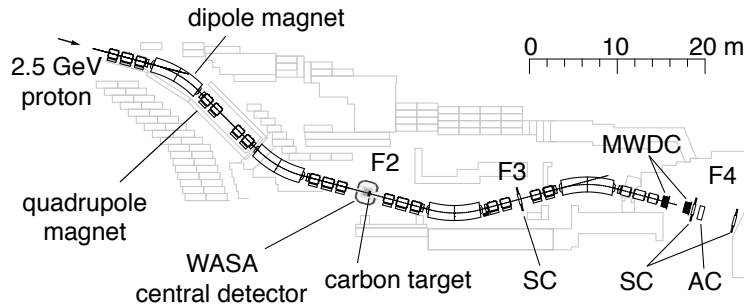


Fig. 2. A schematic view of the experimental setup with the fragment separator FRS and the WASA central detector. See the texts for details.

2.2. Simulation Results

In order to evaluate the experimental sensitivity with the proposed method, we performed simulations for two sets of η' -nucleus potential parameters $(V_0, W_0) = (-90, -17)$ MeV and $(-45, -5.5)$ MeV. The formation cross sections of η' -mesic nuclei decomposed into different decay modes were taken from theoretical calculations [10, 23]. The cross section of the physical background in the (p, d) reaction has been measured in the first inclusive experiment [12, 13]. Emitted particles from the residual nuclei were simulated by using an intra-nuclear cascade code JAM [24, 25].

Figure 3 shows simulated excitation-energy spectra of ^{11}C relative to the η' -meson production threshold. A proton with a momentum larger than 1.0 GeV/ c and an emission angle θ_p in a range of $-0.9 < \cos \theta_p < 0.0$ was requested in the analysis of the simulation data. The black points show the simulated spectra, while the red and blue curves display the components of the signal process associated with η' mesons and the physical background process, respectively. In the upper row, we assumed the acceptance of FRS for the forward deuterons and a data collection time of 4 days, which corresponds to the proposed experiment at GSI [19]. As seen in the figure, indications of peak structures due to the formation of the η' -mesic states can be expected for these two potential parameter sets. Furthermore, in the lower row, we assumed a 20-day beam time with Super-FRS [26] in the future facility FAIR. In this case, prominent peak structures are expected, which enable precise measurements of η' -mesic nuclei.

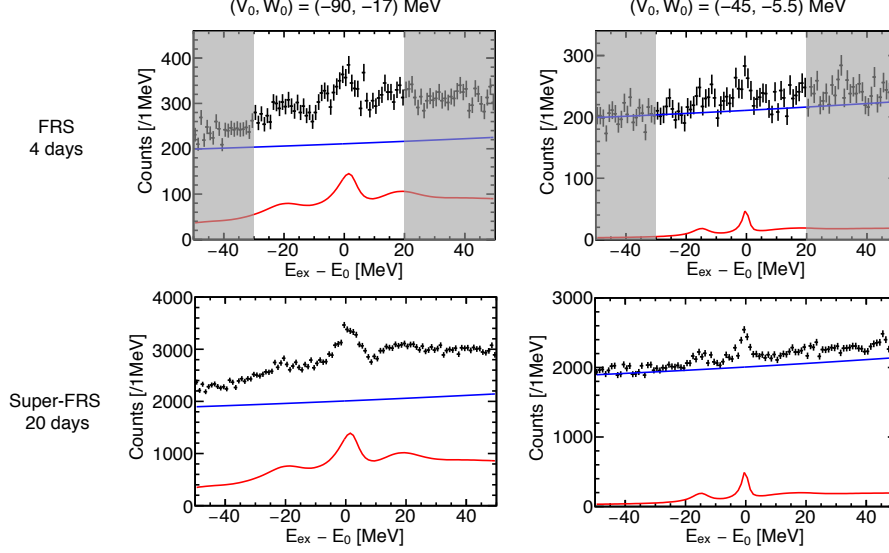


Fig. 3. Simulated spectra for η' -nucleus potential parameters of $(V_0, W_0) = (-90, -17)$ MeV (left) and $(-45, -5.5)$ MeV (right). The abscissa shows the excitation-energy E_{ex} of ^{11}C relative to the η' -meson production threshold E_0 . The black points are the simulated spectra, whereas the red and blue curves are the signal and the physical background components, respectively. A 4 (20)-day beam time with FRS (Super-FRS) is assumed in the upper (lower) panels.

2.3. Preparation Status

We have transported the WASA central detector from Forschungszentrum Jülich, where WASA had been operated from 2006 to 2015, to GSI in Darmstadt. The mini drift chamber has been set up again at GSI and tested with cosmic-ray particles. The plastic scintillator barrel (PSB) will be updated by additionally attaching multi-pixel photon counters (MPPCs) to read out photons at both ends of the scintillator. We have developed a prototype of the new PSB and performed a systematic evaluation of its time resolution by using a 1.7 GeV proton beam at the cooler synchrotron COSY in Forschungszentrum Jülich. Preparations for operation of the superconducting solenoid magnet at GSI are currently underway. We are planning to assemble the full WASA central detector in 2020 and aim at starting the physics run in 2021.

3. Summary

We plan to perform a semi-exclusive measurement of the $^{12}\text{C}(p,dp)$ reaction to search for η' -mesic nuclei. The WASA central detector will be

integrated with the fragment separator FRS to enable this new type of experiment. Preparations and developments on the integration of the WASA central detector into the FRS are currently ongoing. The first physics run is expected in 2021.

REFERENCES

- [1] V. Metag, M. Nanova and E. Ya. Paryev, *Prog. Part. Nucl. Phys.* **97**, 199 (2017).
- [2] S. D. Bass and P. Moskal, *Rev. Mod. Phys.* **91**, 015003 (2019).
- [3] D. Jido, H. Nagahiro, and S. Hirenzaki, *Phys. Rev. C* **85**, 032201(R) (2012).
- [4] Su H. Lee and T. Hatsuda, *Phys. Rev. D* **54**, 1871 (1996).
- [5] P. Costa, M. C. Ruivo, C. A. de Sousa, and Yu. L. Kalinovsky, *Phys. Rev. D* **71**, 116002 (2005).
- [6] H. Nagahiro, M. Takizawa, and S. Hirenzaki, *Phys. Rev. C* **74**, 045203 (2006).
- [7] S. Sakai and D. Jido, *Phys. Rev. C* **88**, 064906 (2013).
- [8] S. D. Bass and A. W. Thomas, *Phys. Lett. B* **634**, 368 (2006).
- [9] H. Nagahiro and S. Hirenzaki, *Phys. Rev. Lett.* **94**, 232503 (2005).
- [10] H. Nagahiro *et al.*, *Phys. Rev. C* **87**, 045201 (2013).
- [11] K. Itahashi *et al.*, *Prog. Theor. Phys.* **128**, 601 (2012).
- [12] Y. K. Tanaka *et al.*, *Phys. Rev. Lett.* **117**, 202501 (2016).
- [13] Y. K. Tanaka *et al.*, *Phys. Rev. C* **97**, 015202 (2018).
- [14] H. Nagahiro, S. Hirenzaki, E. Oset, and A. Ramos, *Phys. Lett. B* **709**, 87 (2012).
- [15] M. Nanova *et al.*, *Phys. Lett. B* **727**, 417 (2013).
- [16] M. Nanova *et al.*, *Phys. Rev. C* **94**, 025205 (2016).
- [17] M. Nanova *et al.*, *Phys. Lett. B* **710**, 600 (2012).
- [18] S. Friedrich *et al.*, *Eur. Phys. J. A* **52**, 297 (2016).
- [19] K. Itahashi *et al.*, Experimental Proposal to FAIR phase 0 at GSI, S457 (2017).
- [20] H. Geissel *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **70**, 286 (1992).
- [21] C. Bargholtz *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **594**, 339 (2008).
- [22] H.-H. Adam *et al.* (WASA-at-COSY Collaboration), arXiv:nucl-ex/0411038.
- [23] H. Nagahiro, *Nucl. Phys. A* **914**, 360 (2013).
- [24] Y. Nara, N. Otuka, A. Ohnishi, K. Niita, and S. Chiba, *Phys. Rev. C* **61**, 024901 (1999).
- [25] Y. Higashi, Master's thesis, Nara Women's University, 2015 (unpublished).
- [26] H. Geissel *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **204**, 71 (2003).