Nuclear Instruments and Methods in Physics Research B 542 (2023) 22–25

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, B

journal homepage: www.elsevier.com/locate/nimb

The WASA-FRS project at GSI and its perspective[☆]

T.R. Saito [1,2,3,*,a], P. Achenbach [4,5], H. Alibrahim Alfaki [2], F. Amjad [2], M. Armstrong [2,6], K.-H. Behr [2], J. Benlliure [7], Z. Brencic [8,9], T. Dickel [2,10], V. Drozd [2,11], S. Dubey [2], H. Ekawa [1], S. Escrig [12,1], M. Feijoo-Fontán [7], H. Fujioka [13], Y. Gao [1,14,15], H. Geissel [2,10], F. Goldenbaum [16], A. Graña González [7], E. Haettner [2], M.N. Harakeh [11], Y. He [1,3], H. Heggen [2], C. Hornung [2], N. Hubbard [2,17], K. Itahashi [18,19,b], M. Iwasaki [18,19], N. Kalantar-Nayestanaki [11], A. Kasagi [1,20], M. Kavatsyuk [11], E. Kazantseva [2], A. Khreptak [21,22], B. Kindler [2], R. Knoebel [2], H. Kollmus [2], D. Kostyleva [2], S. Kraft-Bermuth [23], N. Kurz [2], E. Liu [1,14,15], B. Lommel [2], V. Metag [10], S. Minami [2], D.J. Morrissey [24], P. Moskal [22,25], I. Mukha [2], A. Muneem [1,26], M. Nakagawa [1], K. Nakazawa [20], C. Nociforo [2], H.J. Ong [14,27,28], S. Pietri [2], J. Pochodzalla [4,5], S. Purushothaman [2], C. Rappold [12], E. Rocco [2], J.L. Rodríguez-Sánchez [7], P. Roy [2], R. Ruber [29], S. Schadmand [2], C. Scheidenberger [2,10], P. Schwarz [2], R. Sekiya [30,18,19], V. Serdyuk [16], M. Skurzok [22,25], B. Streicher [2], K. Suzuki [2,31], B. Szczepanczyk [2], Y.K. Tanaka [1,c], X. Tang [14], N. Tortorelli [2], M. Vencelj [8], H. Wang [1], T. Weber [2], H. Weick [2], M. Will [2], K. Wimmer [2], A. Yamamoto [32], A. Yanai [33,1], J. Yoshida [1,34], J. Zhao [2,35]

[1] *High Energy Nuclear Physics Laboratory, RIKEN Cluster for Pioneering Research, RIKEN, 351-0198 Wako, Saitama, Japan*
[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[3] *School of Nuclear Science and Technology, Lanzhou University, 730000 Lanzhou, China*
[4] *Institute for Nuclear Physics, Johannes Gutenberg University, 55099 Mainz, Germany*
[5] *Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*
[6] *Institut für Kernphysik, Universität Köln, 50923 Köln, Germany*
[7] *Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain*
[8] *Jozef Stefan Institute, 1000 Ljubljana, Slovenia*
[9] *University of Ljubljana, 1000 Ljubljana, Slovenia*
[10] *Universität Gießen, 35392 Gießen, Germany*
[11] *University of Groningen, 9747 AA Groningen, The Netherlands*
[12] *Instituto de Estructura de la Materia - CSIC, 28006 Madrid, Spain*
[13] *Tokyo Institute of Technology, 152-8550 Tokyo, Japan*
[14] *Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, China*
[15] *School of Nuclear Science and Technology, University of Chinese Academy of Sciences, 100049 Beijing, China*
[16] *Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[17] *Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[18] *Meson Science Laboratory, Cluster for Pioneering Research, RIKEN, 2-1 Hirosawa, 351-0198 Wako, Saitama, Japan*
[19] *Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, 351-0198 Wako, Saitama, Japan*
[20] *Graduate School of Engineering, Gifu University, 501-1193 Gifu, Japan*
[21] *INFN, Laboratori Nazionali di Frascati, Frascati, 00044 Roma, Italy*
[22] *Institute of Physics, Jagiellonian University, 30-348 Kraków, Poland*
[23] *TH Mittelhessen University of Applied Sciences, 35390 Gießen, Germany*
[24] *National Superconducting Cyclotron Laboratory, Michigan State University, MI 48824, East Lansing, USA*
[25] *Center for Theranostics, Jagiellonian University, 30-348 Krakow, Poland*
[26] *Faculty of Engineering Sciences, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, 23640 Topi, Pakistan*
[27] *Joint Department for Nuclear Physics, Lanzhou University and Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, China*
[28] *Research Center for Nuclear Physics, Osaka University, 567-0047 Osaka, Japan*
[29] *Uppsala University, 75220 Uppsala, Sweden*

☆ The WASA-FRS Collaboration and the Super-FRS Experiment Collaboration.

* Corresponding author at: High Energy Nuclear Physics Laboratory, RIKEN Cluster for Pioneering Research, RIKEN, 351-0198 Wako, Saitama, Japan.
E-mail address: takehiko.saito@riken.jp (T.R. Saito).

a Spokesperson of the S447 experiment.
b Spokesperson of the S490 experiment.
c Co-spokesperson of the S490 experiment.

https://doi.org/10.1016/j.nimb.2023.05.042
Received 3 February 2023; Received in revised form 11 May 2023; Accepted 11 May 2023
Available online 14 June 2023
0168-583X/

[30] Kyoto University, 606-8502 Kyoto, Japan
[31] Ruhr-Universiät Bochum, Institut für Experimentalphysik I, 44780 Bochum, Germany
[32] KEK, 305-0801 Tsukuba, Ibaraki, Japan
[33] Saitama University, Sakura-ku, 338-8570 Saitama, Japan
[34] Tohoku University, 980-8578 Sendai, Japan
[35] Peking University, 100871 Beijing, China

ARTICLE INFO

Keywords:
Fragment separator
WASA central detector
Hypernuclei
Mesic-nuclei

ABSTRACT

A novel technique to study bound states of exotic hadrons in subatomic nuclei, such as hypernuclei and mesic nuclei, has been developed by employing the Fragment Separator FRS and the WASA central detector at GSI. Two experiments, S447 for studying light hypernuclei, especially hypertriton and a Λnn bound state, and S490 for searching for η' mesic-nuclei, were recently performed. Data analyses are currently in progress, and light charged particles such as protons and $\pi^{\pm}$ are clearly observed and identified in the both experiments. For S447, light nuclear fragments that can also be residual nuclei from decays of hypernuclei of interests have been analysed by the FRS, and a momentum resolution, $\Delta p/p$, of 5×10^{-4} has been achieved. Further data analyses are to be completed. The WASA-FRS project will be continued and extended with the FRS at FAIR Phase 0, and upgrading of the WASA magnet and detectors is currently in progress. Furthermore, construction of a larger detector system with the Super-FRS at FAIR Phase 1 is also under consideration.

1. Introduction

Interactions among hadrons and their properties, like the masses and lifetimes, can be studied via exotic hadron-nucleus bound states. Among those states, there have been much attentions on hypernuclei [1–4] and meson-nucleus bound states including mesic-atoms and mesic-nuclei [5–9].

In the field of hypernuclear physics, few-body hypernuclei have again recently attracted experimentalists and theoreticians. The lightest known hypernucleus, the hypertriton, was experimentally studied until the 1970s by using nuclear emulsions and bubble chambers, which concluded that a Λ hyperon is very weakly bound to a deuteron core with a small binding energy of 0.13 ± 0.05 MeV [10,11]. Therefore, the lifetime of the hypertriton has been considered to be very close to the lifetime of a free Λ hyperon, i.e., 263 ps [12], without having precise experimental data. However, recent experiments employing heavy ion beams have shown much or slightly shorter lifetime values of hypernuclei than that of the free Λ hyperon [13–20], and the measured values have a large span for measurements obtained even by one collaboration. Another type of three-body hypernuclear states have also become to be of special interest. The HypHI collaboration observed an enhancement in the invariant mass distributions of the d+π^- and t+π^- final states indicating a possibility of existence of an unprecedented neutral bound state formed by a Λ hyperon and two neutrons, i.e., Λnn [21]. A large theoretical effort has been made to study this state within various approaches and models [22–25], however, the obtained results did not show that the system Λnn is bound. On the other hand, pionless effective field theory studying the Λnn state with $I = 0$ has not ruled out the bound state [26,27]. Very recently, the E12-17-003 experiment was performed at JLab to search for Λnn bound and resonance state [25,28] by employing electron beams to bombard a tritium target, and an indication of the existence of the Λnn state has been observed with small significance [29]. It should be, however, noted that the same collaboration published different interpretations of the data, which suggest non-existence of Λnn [30], therefore, a conclusion has not been reached yet. The existence of the Λnn should be thus further studied experimentally with better precision and more data samples.

For studying mesic-nucleus bound states, a special attention has been paid on searching for η'-nuclei since their spectroscopy could provide information of the strong interaction leading to understanding of the origin of the mass of the η' meson. The first experiment at GSI aimed at observing η' meson bound states in carbon nucleus for studying in-medium η' meson properties [31,32]. While the existence of such bound states has been theoretically predicted for various cases of η'-nucleus potentials [33–38], no experimental observation was reported so far [31,32,39].

We are challenging to solve puzzles related to three-body hypernuclear states and to search for η'-nuclei, and therefore, the present work has developed a novel technique to study three-body hypernuclei and to search for η'-nuclei by employing the GSI fragment separator (FRS) [40] as a high momentum-resolution forward magnetic spectrometer and the WASA central detector [41].

2. The WASA-FRS experiments

A schematic layout of the FRS [40] is presented in Fig. 1. Inside of the mid focal plane (F2) of the FRS indicated by a red circle in the figure, the WASA central detector [41] is mounted. The WASA central detector that is used in our experiment consists of a superconducting solenoid magnet (up to 1 T magnetic field) with its associated iron yokes and a cryogenic system, a calorimeter with CsI crystals (SEC), an inner drift chamber with straw tubes (MDC), and newly developed arrays of plastic barrel hodoscopes (PSB) [42] and end-cap hodoscopes (PSFE and PSBE) [43]. We performed two experiments in 2022, S490 for searching for η'-nuclei and S447 for studying hypernuclei, and experimental configurations at the F2 section of the FRS for these experiments are presented in the (a) and (b) of Fig. 2, respectively.

The experiment for searching for η'-nuclei (S490) employed proton beams at 2.5 GeV with an intensity up to $\sim 3 \times 10^8$ pps bombarded at a carbon target with a thickness of 4 g/cm^2. The target was installed in the inner beam pipe of the inner drift chamber, MDC, as shown in Fig. 2(a). An η'-mesic ^{11}C nuclei is to be populated in the ^{12}C(p,d) reaction occurred in the target. Deuterons emitted to the forward directions are transferred and analysed in the F2–F4 section of the FRS. Particles emitted from decays of mesic-nuclei of interest, in particular, protons emitted to backward directions, are measured by the WASA detectors. It is expected that a signal-to-noise ratio could be improved by approximately a factor of 100 in the present work in comparison to the previous measurements [31,32]. We have recorded approximately 1×10^7 events of the ^{12}C(p,d) reaction in a data collection time of 62 h.

The configuration of the experimental setup for studying hypernuclei (S447, WASA-FRS-HypHI) is shown in Fig. 2(b). In addition to the conventional WASA setup employed in the experiment searching for η'-nuclei (S490), additional scintillating fibre detectors are mounted [43]. Three fibre detector stations, UFT1,2, and 3, were mounted in front of the WASA detectors, and two fibre detector stations, DFT 1 and 2, were placed behind the WASA detector. The Mini-fibre detector composed by two fibre complexes (MFT1 and 2) was located inside the iron yoke of the WASA superconducting solenoid magnet. A small hodoscope composed by small plastic scintillator fingers (referred as Start counter

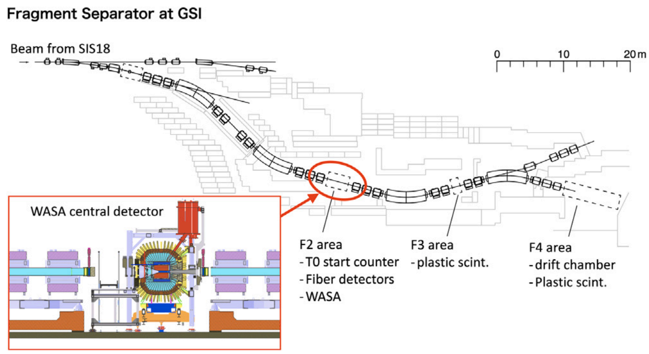

Fig. 1. The Fragment Separator (FRS) and the WASA detector.

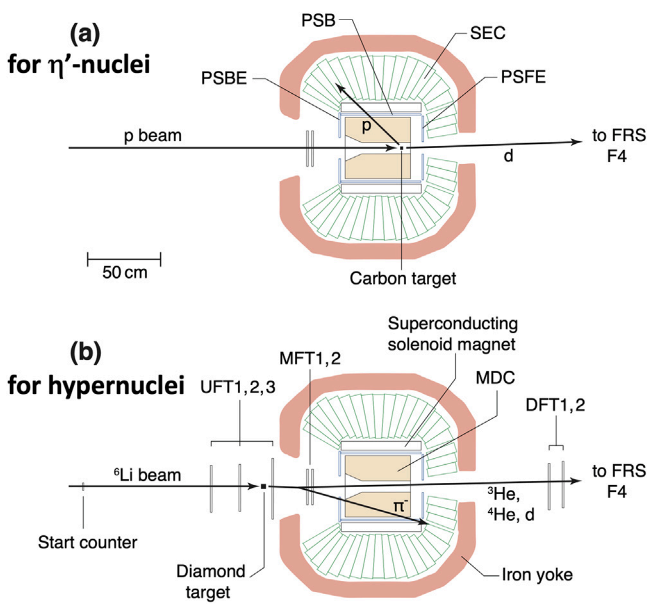

Fig. 2. Experimental configurations of the S490 experiment for searching for η'-nuclei (a) and the S447 experiment for studying hypernuclei (b).

in the figure) was mounted in front of the UFT1 to measure beam particles. Hypernuclei of interest including the hypertriton and states associated with Λnn are produced by ^{6}Li and ^{12}C beams at 1.96 A GeV bombarded at a diamond target with a thickness of 9.87 g/cm^2 located between the UFT2 and 3. Negatively charged pions from decays of hypernuclei are measured by the WASA detectors with the MFT1 and 2, and residual nuclei of hypernuclear decays are transferred to and analysed by the F2–F4 sections of the FRS. In the present work, the particle rate at F4 of the FRS can be controlled under a few thousands Hz, and it is sufficiently small to take data only with a requirement of particle detection at F4. Therefore, it provides an opportunity to implement a simpler data-acquisition system without a complicated displaced vertex trigger, as employed in the HypHI [13]. It should be noted that the standard resolving power of the FRS is for the measurement of the momentum of the residual nuclei is approximately three orders of magnitude better than the former HypHI experiment in 2009. Details of the experimental concept and related Monte Carlo simulations were already discussed in Ref. [44]. We have recorded 3.3×10^8 events with ^{3}He at F4, 0.9×10^9 events with ^{4}He at F4 and 1.8×10^8 events with deuterons at F4 by using ^{6}Li projectiles, in time periods of 40.9, 43.9 and 43.9 h, respectively. Additionally, we recorded data with ^{12}C beams with an amount of 1.0×10^8 events with ^{3}He at F4 and 2.4×10^5 events with ^{9}C at F4 for 13.5 h.

Fig. 3 shows photographs of the WASA-FRS setup at F2 of the FRS.

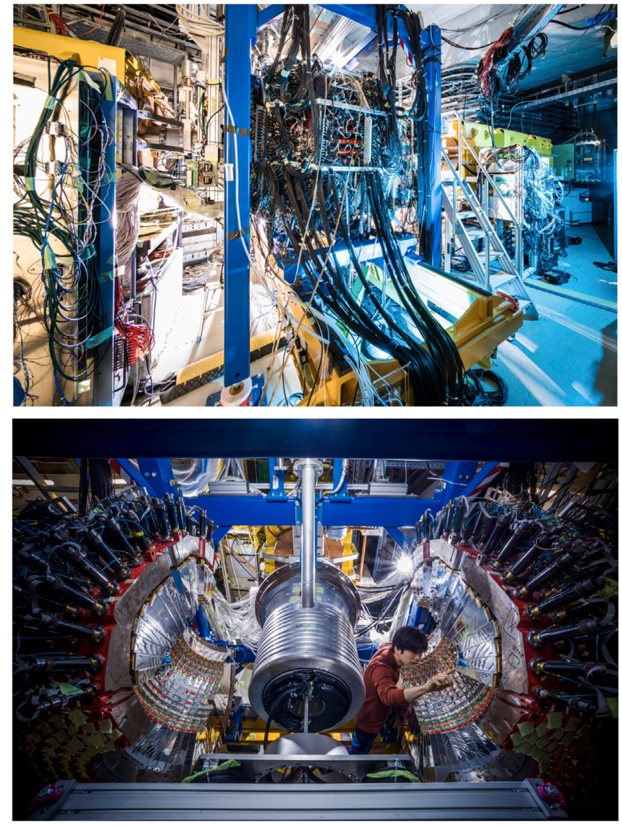

Fig. 3. Photographs of the WASA setup with a side view (top) and the iron-yoke opened (bottom). The photos are provided by Jan Hosan and GSI/FAIR.

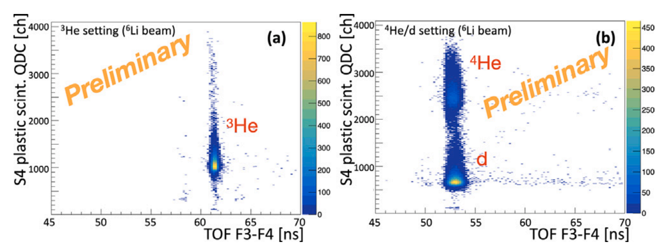

Fig. 4. Correlations between QDC values of the plastic scintillator at F4, which corresponds to the energy deposition of particles of interest in the scintillator, and the Time-of-Flight in F3–F4, with the magnetic rigidity of the FRS optimised to observe ^{3}He from the hypertriton decay (panel (a)) and ^{4}He and deuterons from decays of $^4_\Lambda$H and Λnn (panel (b)).

3. Preliminary results of data analyses

Data analysis for the experiments, S447 and S490, is in progress. For the S447 experiments studying hypernuclei, particle identification for residual nuclei from decays of hypernuclei, have been made. Fig. 4(a) shows a correlation between QDC values of the plastic scintillator at F4, which corresponds to the energy deposition of particles of interest in the scintillator, and the Time-of-Flight in F3–F4, with the magnetic rigidity of the FRS optimised to observe ^{3}He from the hypertriton decay. It shows clearly a distribution of ^{3}He. Panel (b) of the same figure shows a similar plot with the magnetic rigidity of the FRS optimised for detecting ^{4}He and deuterons from decays of $^4_\Lambda$H and Λnn, and their clear distributions and a good separation between them are observed. It has preliminary been deduced that a momentum resolution $\Delta p/p$ for observed fragments in F2–F4 of the FRS is approximately 5×10^{-4} which is very close to the designed value of the experiment. Tracking analysis of charged particles penetrating the WASA detector under a

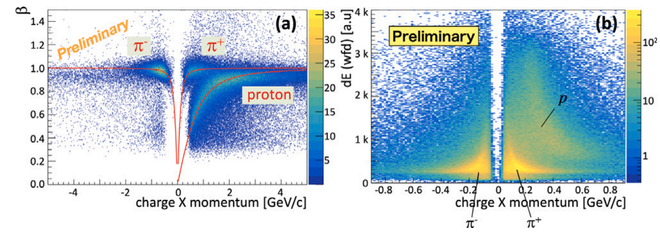

Fig. 5. Distributions of charged particles obtained by tracking with the WASA central and associated detectors at F2 of the FRS. Panel (a): a velocity factor β as a function of values of charge×momentum for charged particles with the magnetic setup of the FRS for observing ^{3}He from hypertritons in the S447 experiment. Charged particle tracking is performed by using hit information in the MFT1, MFT2, MDC and the plastic scintillator barrel PSB. Panel (b): a correlation between the energy deposition ΔE measured by the PSB and values of charge×momentum for charged particles deduced by tracking with the MDC and PSB.

magnetic field (1 T at the centre of the solenoid magnet) has also been being in progress by using the Kalman filter with the GENFIT tracking tool [45]. Fig. 5(a) shows a velocity factor β as a function of values of charge×momentum for charged particles with the magnetic setup of the FRS for observing ^{3}He from hypertritons in the S447 experiment. Charged particle tracking is performed by using hit information in the MFT1, MFT2, MDC and the plastic scintillator barrel PSB. Distributions of protons and $\pi^{\pm}$ are clearly shown. Particle tracking and identification in the analyses of the S490 experiment searching for η'-nuclei has been performed in a different manner since the carbon target is installed inside the WASA central detector and since only the WASA central detector was used for measuring charged particles. Fig. 5(b) shows a correlation between the energy deposition ΔE measured by the PSB and values of charge×momentum for charged particles deduced by tracking with the MDC and PSB. Clear distributions of protons and $\pi^{\pm}$ are also shown. Further data analyses for the both experiments, S447 and S490, are in progress, and they will be completed soon.

4. Perspective

Experimental activities with the WASA-FRS setup will be continued at FAIR Phase 0. We are currently working for upgrading the superconducting solenoid magnet to achieve a maximum magnetic field of 1.5–2.0 T, and we are also planning to use an electric cooling system for easier operations. The increase of the magnetic field is especially important for studying hypernuclei because charged K-mesons can clearly be observed and identified with $>$ 1.5 T. Developments of planner drift chambers inside the solenoid magnet is also in progress. The project will be extended with the Super-FRS at FAIR Phase 1, and construction of a larger detector system is under consideration. With the continued experimental efforts at FAIR Phase 0 and 1, the collaboration will perform further studies of mesic nuclei and exotic hypernuclei including proton-rich [46] and neutron-rich [47] hypernuclei. Furthermore, studies of baryonic resonances in exotic nuclei will be foreseen.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The two WASA-FRS experiments, S447 and S490 were performed in 2022 at the FRS at the GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase 0. The authors would like to acknowledge the GSI staff for their supports in the experiment. The WASA-FRS project is supported by the JSPS KAKENHI (Grant Numbers JP18H01242), the JSPS Grant-in-Aid for Early-Career Scientists (Grant No. JP20K14499), the JSPS Fostering Joint International Research (B) (Grant No. JP20KK0070), Proyectos I+D+i 2020 ref: PID2020-118009GA-I00; grant 2019- T1/TIC-13194 of the program Atracción de Talento Investigador of the Community of Madrid, the Regional Government of Galicia under the Postdoctoral Fellowship Grant No. ED481D-2021-018, the SciMat and qLife Priority Research Areas budget under the program Excellence Initiative - Research University at the Jagiellonian University and the European Unions Horizon 2020 research and innovation programme under grant agreement No. 824093. The project is also supported by the Justus-Liebig-Universität (JLU), Gießen, Germany, and GSI under the JLU-GSI strategic Helmholtz partnership agreement. The authors thank Luise Doersching-Steitz of GSI, Rita Krause of GSI, Yukiko Kurakata of RIKEN, Daniela Press of GSI, Miao Yang of IMP and Xiaohua Yuan of IMP for supporting the projects, including the administrative works.

References

[1] D.H. Davis, Nuclear Phys. A 754 (2005) 3.
[2] R.H. Dalitz, Nuclear Phys. A 754 (2005) 14.
[3] O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.
[4] A. Feliciello, T. Nagae, Rep. Progr. Phys. 78 (2015) 096301.
[5] T. Yamazaki, et al., Phys. Rep. 514 (2012) 1.
[6] R.S. Hayano, T. Hatsuda, Rev. Modern Phys. 82 (2010) 2949.
[7] D. Gotta, Prog. Part. Nucl. Phys. 52 (2004) 133.
[8] V. Metag, M. Nanova, E. Ya Paryev, Prog. Part. Nucl. Phys. 97 (2017) 199.
[9] S.D. Bass, P. Moskal, Rev. Modern Phys. 91 (2019) 015003.
[10] G. Bohm, et al., Nuclear Phys. B 4 (1968) 511.
[11] M. Juric, et al., Nuclear Phys. B 52 (1973) 1.
[12] Particle Data Group, et al., Prog. Theor. Exp. Phys. 2020 (2020).
[13] C. Rappold, et al., Nuclear Phys. A 913 (2013) 170.
[14] The STAR collaboration, Science 328 (2010) 58.
[15] Y. Xu, the STAR Collaboration, Proc. 12th Int. Conf. on Hypernucl. Strange Part. Phys. (HYP2015) (2017) 021005.
[16] L. Adamczyk, et al., Phys. Rev. C 97 (2018) 054909.
[17] J. Chen, et al., Phys. Rep. 760 (2018) 1.
[18] M.S. Abdallah, et al., Phys. Rev. Lett. 128 (2022) 202301.
[19] J. Adam, et al., Phys. Lett. B 754 (2016) 360.
[20] S. Acharya, et al., Phys. Lett. B 797 (2019) 134905.
[21] C. Rappold, et al., Phys. Rev. C 88 (2013) 041001.
[22] E. Hiyama, et al., Phys. Rev. C 89 (2014) 061302.
[23] A. Gal, et al., Phys. Lett. B 736 (2014) 93.
[24] H. Garcilazo, et al., Phys. Rev. C 89 (2014) 057001.
[25] M. Sch¨ afer, et al., Phys. Lett. B 808 (2020) 135614.
[26] S.-I. Ando, et al., Phys. Rev. C 92 (2015) 024325.
[27] F. Hildenbrand, et al., Phys. Rev. C 100 (2019) 034002.
[28] I.R. Afnan, et al., Phys. Rev. C 92 (2015) 054608.
[29] B. Pandey, et al., Phys. Rev. C 105 (2022) L051001.
[30] K. Itabashi, et al., Few Body Syst. 63 (2022) 16, K.N. Suzuki, others, PTEP 2022(2022)Issue 1, 013D01.
[31] Y.K. Tanaka, et al., Phys. Rev. Lett. 117 (2016) 202501.
[32] Y.K. Tanaka, et al., Phys. Rev. C 97 (2018) 015202.
[33] H. Nagahiro, S. and Hirenzaki, Phys. Rev. Lett. 94 (2005) 232503.
[34] H. Nagahiro, M. Takizawa, S. Hirenzaki, Phys. Rev. C 74 (2006) 045203.
[35] S. Sakai, D. Jido, Phys. Rev. C 88 (2013) 064906.
[36] S.D. Bass, A.W. Thomas, Phys. Lett. B 634 (2006) 368.
[37] D. Jido, H. Nagahiro, S. Hirenzaki, Phys. Rev. C 85 (2012) 032201(R).
[38] H. Nagahiro, et al., Phys. Rev. C 87 (2013) 045201.
[39] N. Tomida, et al., Phys. Rev. Lett. 124 (2020) 202501.
[40] H. Geissel, et al., Nucl. Instrum. Methods Phys. Res. B 70 (1992) 286.
[41] C. Bargholtz, et al., Nucl. Instrum. Methods Phys. Res. A 594 (2008) 339.
[42] R. Sekiya, et al., Nucl. Instrum. Methods Phys. Res. A 1034 (2022) 166745.
[43] H. Ekawa, WASA-FRS collaboration, EPJ Web Conf. 271 (2022) 08012.
[44] T.R. Saito, et al., Nat. Rev. Phys. 3 (2021) 803.
[45] T. Bilka, et al., Arxiv 1902.04405, 2019.
[46] C. Rappold, et al., Phys. Rev. C 94 (2016) 044616.
[47] T.R. Saito, et al., Euro. Phys. J. A 57 (2021) 159.