

Nuclear Science Research Division Few-body Systems in Physics Laboratory

1. Abstract

Unlike many-body systems, few-body systems can be described with microscopic theories that can be solved without approximations. To this end the laboratory uses numerical techniques to exactly solve the equations describing few-body quantum systems. In particular, an accurate calculation method called the ‘Gaussian Expansion Method using infinitesimally shifted Gaussian lobe basis function’ has been developed. This method makes calculations tractable up to five bodies even with complicated interactions. It has been applied to various three-, four- and five-body calculations in hypernuclei, light nuclear systems, as well as cold-atom systems. These calculations have provided new insights into these various fields of physics.

2. Major Research Subjects

- (1) Structure of hypernuclei
- (2) Neutron-rich nuclei
- (3) Few-body universality in nuclear and atomic systems
- (4) Structure of exotic hadron system

3. Summary of Research Activity

(1) Hypernuclei

We calculated the energy spectra of the neutron-rich He Λ hypernuclei with $A = 6$ to 9 within the framework of an $\alpha + \Lambda + X \times n$ ($X = 1-4$) cluster model using the cluster orbital shell model. The employed constituent particles reproduce their observed properties. For resonant states of core nuclei such as ${}^5\text{He}$, ${}^6\text{He}$, and ${}^7\text{He}$, the complex scaling method is employed to obtain energies and decay widths. The calculated ground states of ${}^6_\Lambda\text{He}$ and ${}^7_\Lambda\text{He}$ are in good agreement with published data. The energy levels of ${}^8_\Lambda\text{He}$ and ${}^9_\Lambda\text{He}$ are predicted. In ${}^9_\Lambda\text{He}$, we find one deeply bound state and two excited resonant states, which are proposed to be produced at the Japan proton accelerator research complex (J-PARC) by the double-charge-exchange reaction (π^- , K^+) using a ${}^9\text{Be}$ target.

(2) Neutron-rich nuclei

Motivated by a sharp peak observed by studying four neutron energy distribution, we investigate a reaction model. As a result, we conclude that observed peak is consequence of dineutron-dineutron correlation.

(3) Exotic hadron systems

We have used chiral effective theories of diquarks and quark-diquark to investigate doubly heavy tetraquarks $Q_{q\bar{q}}$ and singly heavy baryons Q_{qq} . We also used extended quark models to investigate the fully charmed tetraquark resonant states $cc\bar{c}\bar{c}$ as well as p -wave B_S states. From these calculations, we could reproduce some experimental data and make predictions for unobserved states. In addition, we investigated the hadron mass spectrum of two-color QCD at finite density using the linear sigma model, as well as lattice calculations. Other research activities include the study of SU(N) Yang-Mills theory and the Dirac Kondo effect under magnetic catalysis.

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List of Publications & Presentations**Publications****[Original Papers]**

- T. Myo and E. Hiyama, "Structure of neutron-rich He Λ hypernuclei using the cluster orbital shell model," *Phys. Rev. C* **107**, 054302 (2023).
- Q. Meng, E. Hiyama, M. Oka, A. Hosaka, and C. Xu, "Doubly heavy tetraquarks including one-pion exchange potential," *Phys. Rev. B* **846**, 138221 (2023).
- A. Yamamoto and T. Doi, "Toward nuclear physics from lattice QCD on quantum computers," *Prog. Theor. Exp. Phys.* **2024**, 033D02 (2024), arXiv:2211.14550 [hep-lat].
- E. Chizzali, Y. Kamiya, R. D. Grande, T. Doi, L. Fabbietti, T. Hatsuda, and Y. Lyu, "Indication of a p - ϕ bound state from a correlation function analysis," *Phys. Lett. B* **848**, 138358 (2024), arXiv:2212.12690 [nucl-ex].
- Y. Lyu, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, and J. Meng, "Doubly charmed tetraquark T_{cc}^+ from lattice QCD near physical point," *Phys. Rev. Lett.* **131**, 161901 (2023) [Editors' Suggestion], arXiv:2302.04505 [hep-lat].
- K. Murakami, Y. Akahoshi, S. Aoki, T. Doi, and K. Sasaki (HAL QCD Collaboration), "Lattice quantum chromodynamics (QCD) studies on decuplet baryons as meson-baryon bound states in the HAL QCD method," *Prog. Theor. Exp. Phys.* **2023**, 043B05 (2023) [Editor's Choice], arXiv:2210.05395 [hep-lat].
- P. Naidon, "Universal geometry of two-neutron halos and Borromean Efimov states close to dissociation," *SciPost Phys.* **15**, 123 (2023).
- H. Takada, D. Suenaga, M. Harada, A. Hosaka, and M. Oka, "Axial anomaly effect to three-quark and five-quark singly heavy baryons," *Phys. Rev. D* **108**, 054033-1–15 (2023).
- Q. Meng, E. Hiyama, M. Oka, A. Hosaka, and C. Xu, "Doubly heavy tetraquarks including one-pion exchange potential," *Phys. Lett. B* **846**, 138221-1–6 (2023).
- G. -J. Wang, M. Oka, and D. Jido, "Quark Confinement for multi-quark systems—Application to fully-charmed tetraquarks—," *Phys. Rev. D* **108**, L071501-1–6 (2023).
- D. Suenaga and M. Oka, "Axial anomaly effect to the chiral-partner structure of diquarks at high temperature," *Phys. Rev. D* **108**, 014030-1–18 (2023).
- A. J. Arifi, L. Happ, S. Ohno, and M. Oka, "Structure of heavy mesons in the light-front quark model," Arxiv:2401.07933.

- A. J. Arifi, H. M. Choi, and C. R. Ji, “Pseudoscalar meson decay constants and distribution amplitudes up to twist 4 in the light-front quark model,” *Phys. Rev. D* **108**, 013006 (2023).
- A. J. Arifi, P. T. P. Parada, and K. Tsushima, “In-medium properties of the light and heavy-light mesons in a light-front quark model,” *Phys. Rev. D* **107**, 114010 (2023).
- L. Happ, P. Naidon, and E. Hiyama, “Mass ratio dependence of three-body resonance lifetimes in 1D and 3D,” *Few-Body Syst.* **65**, 38 (2024).
- K. Hattori, D. Suenaga, K. Suzuki, and S. Yasui, “Dirac Kondo effect under magnetic catalysis,” *Phys. Rev. B* **108**, 245110 (2023).
- D. Suenaga and M. Oka, “Axial anomaly effect on the chiral-partner structure of diquarks at high temperature,” *Phys. Rev. D* **108**, 014030 (2023).
- M. Kawaguchi and D. Suenaga, “Fate of the topological susceptibility in two-color dense QCD,” *J. High Energy Phys.* **08**, 189 (2023).
- H. Takada, D. Suenaga, M. Harada, A. Hosaka, and M. Oka, “Axial anomaly effect on three-quark and five-quark singly heavy baryons,” *Phys. Rev. D* **108**, 054033 (2023).
- D. Suenaga, K. Murakami, E. Itou, and K. Iida, “Mass spectrum of spin-one hadrons in dense two-color QCD: Novel predictions by extended linear sigma model,” *Phys. Rev. D* **109**, 074031 (2024).
- S. Ito, D. Yoshida, Y. Kita, T. Shimazaki, and M. Tachikawa, “Stability and bonding nature of positronic lithium molecular dianion,” *J. Phys. Chem.* **158**, 204303 (2023).
- D. Yoshida and M. Tachikawa, “Multi-component configuration interaction study for positron-molecule compounds: Benchmark calculations of positron binding in polar and non-polar molecules,” *Eur. Phys. J. D* **78**, 10 (2024).

[Book]

- W. P. Schleich, I. Tkáčová, and L. Happ, “Insights into complex functions” in *Sketches of Physics: The Celebration Collection (Lecture Notes in Physics)*, R. Citro, M. Lewenstein, A. Rubio, W. P. Schleich, J. D. Wells, G. P. Zank (eds.), Vol. 1000 (Springer, 2023).

[Proceedings]

- M. Ridwan, A. J. Arifi, and T. Mart, “The properties of radially excited charmonia in the light-front quark model,” *ITM Web Conf.* **61**, 01016 (2024).
- M. F. Syahbana, A. J. Arifi, and T. Mart, “Distribution amplitude and decay constant of 1S and 2S state light mesons in the light-front quark model,” *ITM Web Conf.* **61**, 01014 (2024).
- K. Hattori, D. Suenaga, K. Suzuki, and S. Yasui, “Phase diagram of the QCD Kondo effect and inactivation of the magnetic catalysis,” *EPJ Web Conf.* **276**, 01015 (2023).

Presentations

[International Conferences/Workshops]

- E. Hiyama (invited), “Gaussian expansion method and its application to nuclear and atomic physics,” The 1st Conference of Accelerator-Based Science and Technology, Serpong, Indonesia, February 19–22, 2024.
- E. Hiyama (invited), “Gaussian expansion method and its application to nuclear and atomic physics,” Massively Parallel Programming in Quantum Chemistry and Physics (MPQCP 2024), Wako, Japan, January 9–10, 2024.
- E. Hiyama (invited), “Structure of Λ hypernuclei and Λ N interaction,” The Workshop on Physics of Hypernuclei and Hyperon-Nucleon (Λ N) interactions, Huizhou, China, December 18–21, 2023.
- E. Hiyama (invited), “Structure of multi-neutron systems,” FRIB Nuclear Theory Seminar, Michigan, USA, November 15, 2023.
- E. Hiyama (invited), “Structure of neutron-rich nuclei with $t+4n$ cluster model,” Critical Stability of Few-body Quantum Systems, Trento, Italy, October 23–27, 2023.
- E. Hiyama (invited), “Recent progress in hypernuclear physics,” 25th European conference on few-body problems in physics (EFB25), Mainz, Germany, July 30–August 4, 2023.
- E. Hiyama (invited), “Hadron Interaction and exotics,” The 9th Asian Triangle Heavy-Ion Conference (ATHIC 2023), Hiroshima, Japan, April 24–27, 2023.
- T. Doi (invited) for HAL QCD Collaboration, “ N - ϕ interaction from lattice QCD and implication from combined analysis with femtoscopic data,” Fourth International Workshop on the Extension Project for the J-PARC Hadron Experimental Facility (HEF-ex 2024), Tokai (J-PARC), Japan & Online, February 19–21, 2024.
- T. Doi for HAL QCD Collaboration, “Hadron interactions and Exotics from Lattice QCD in the HAL QCD method,” Nagoya Workshop on Exotic Hadrons 2023, Nagoya (Nagoya University), Japan, November 14–17, 2023.
- T. Doi (invited) for HAL QCD Collaboration, “Hadron-hadron interactions from Lattice QCD with the HAL QCD method,” International Workshop on J-PARC Hadron Physics 2023 (J-PARC Hadron 2023), Tokai (J-PARC), Japan, September 12–15, 2023.
- T. Doi (invited) for HAL QCD Collaboration, “Hadron interactions from Lattice QCD,” 34th IUPAP Conference on Computational Physics (CCP2023), Kobe, Japan & Online, August 4–8, 2023.
- P. Naidon (invited), “Borromean three-body Halo universality,” Critical Stability Workshop, ECT*, Trento, Italy, October 25, 2023.
- D. Jido (oral), M. Oka, and G. J. Wang, “Quark confinement and the spectrum of fully-charmed tetraquark,” JPS-APS Joint meeting of Division of Nuclear Physics, Hawaii, USA, November 26–December 1, 2023.
- M. Oka (invited), “Quark confinement and spectrum of fully-charmed tetraquark,” International Workshop on Exotic Hadrons, Nagoya, November 15, 2023.
- M. Oka (invited), “Quark confinement and the spectrum of fully-charmed tetraquark,” International Conference on New Trends in Theo-

- retical Physics, Tashkent (NUUZ), Uzbekistan & Online, October 24, 2023.
- M. Oka (invited), “Spectrum of heavy baryons and roles of diquarks,” International Workshop on J-PARC Hadron Physics 2023, Tokai (KEK), Japan, September 12–15, 2023.
- M. Oka (invited), “Spectroscopy of heavy baryons and roles of diquarks,” The 20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023), Genova, Italy, June 5–10, 2023.
- M. Oka (invited), “Fully-charmed tetraquark and quark confinement,” Yonsei Workshop Series on Nuclear Hadron Physics-3, Seoul (Yonsei University), South Korea, April 6, 2023.
- A. J. Arifi (oral), “Recent progress in light-front quark model,” 1st Conference of Accelerator-Based Sciences and Technology (CAST 2024), Tangerang, Indonesia, February 19–22, 2024.
- A. J. Arifi (oral), “Heavy meson structure in light-front quark model,” 9th International Symposium on Current Progress in Mathematics and Sciences (ISCPMS) 2023, Bali, Indonesia, August 29–30, 2023.
- A. J. Arifi (oral), “In-medium properties of mesons in light-front quark model,” OMEG workshop, Seoul, South Korea, July 12–13, 2023.
- A. J. Arifi (oral), “In-medium properties of mesons in light-front quark model,” Origin of Matter and Masses in the Universe: Hadrons in free space, dense nuclear medium, and compact stars, Pohang, South Korea, July 8–12, 2023.
- A. J. Arifi (oral), “Structure of heavy mesons in light-front quark model,” Hadron 2023 Conference, Genova, Italy, June 5–9, 2023.
- L. Happ, “Lifetime-analysis of three-body resonance states,” 25th European Conference on Few-Body Problems in Physics (EFB25), Mainz, Germany, July 31–August 4, 2023.
- L. Happ (invited), “Can reduced dimensions lead to increased lifetime of three-body resonance states?,” ECT* Workshop, “Critical stability of few-body quantum systems,” Trento, Italy, October 23–27, 2023.
- D. Suenaga (invited), “Pentaquark picture for singly heavy baryons based on a chiral model,” HADRON2023, Genova, Italy, June 5–9, 2023.
- D. Suenaga (oral), “Pentaquark picture of singly heavy baryons from a chiral model,” International Workshop on J-PARC Hadron Physics 2023, Tokai, Japan, September 12–15, 2023.
- D. Suenaga (invited), “QCD Kondo effect under magnetic field,” DNP-JPS meeting, Hawaii, USA, November 26–December 1, 2023.
- D. Suenaga (oral), “Axial anomaly effect to the chiral-partner structure of diquarks at high temperature,” DNP-JPS Meeting, Hawaii, USA, November 26–December 1, 2023.
- D. Yoshida (oral), Y. Kita, T. Shimazaki, and M. Tachikawa, “Positron binding and annihilation properties of hydrogen bonded binary molecular clusters,” The 5th Conference of Theory and Applications of Computational Chemistry (TACC2023), Sapporo, Japan, September 4–9, 2023.
- D. Yoshida (poster), Y. Kita, T. Shimazaki, and M. Tachikawa, “Theoretical study on positron binding and annihilation properties of hydrogen bonded binary molecular clusters,” XXI International Workshop on Low-Energy Positron and Positronium Physics and XXIII International Symposium on Electron-Molecule Collisions and Swarms (POSMOL2023), Notre Dame, Indiana, USA, August 3–6, 2023.
- D. Yoshida (oral) and K. Takahashi, “Danger of using minimum energy pathway for spin crossover reaction: A case study for Ni + CO and Ni + N₂ reactions,” 38th Symposium on Chemical Kinetic and Dynamics (SCKD), Fukuoka, Japan, June 7–9, 2023.

[Domestic Conferences/Workshops]

- 肥山詠美子 (招待講演), “Structure of Xi hypernuclei from view point of theory side,” S-2S Workshop 2023, 京都市 (京都大学), 2023 年 8 月 19–20 日.
- 土井琢身 (招待講演) for HAL QCD Collaboration, “Exotic tetraquark Tcc—Charming cluster from Lattice QCD—,” Clustering as a Window on the Hierarchical Structure of Quantum Systems, 和光市 (理化学研究所), 2023 年 9 月 22–23 日.
- 土井琢身 (招待講演) for HAL QCD Collaboration, “Exotic hadrons from lattice QCD,” Program for Promoting Researches on the Supercomputer Fugaku (Simulation for Basic Science: Approaching the New Quantum Era), 港区 (慶応義塾大学), 2023 年 6 月 20–21 日.
- 山中長閑 (口頭発表), 「磁場中の軽い原子核の構造の変化」, “Constraint on R-parity violating supersymmetry from EDM at the two-loop level,” 日本物理学会 2024 年春季大会, オンライン, 2024 年 3 月 18–21 日.
- A. J. Arifi (口頭発表), “Heavy meson in light-front quark model with Gaussian expansion method,” Strangeness Nuclear Physics School 2023, 東海村 (J-PARC), 2023 年 12 月 11–15 日.
- A. J. Arifi (口頭発表), “Structure of hadrons in light-front quark model,” RIKEN-Tohoku Joint Workshop, 和光市 (理化学研究所), 2023 年 5 月 11–12 日.
- L. Happ (口頭発表), “Universal few-body effects in one dimension,” RIKEN-Tohoku Joint Workshop, 和光市 (理化学研究所), 2023 年 5 月 11–12 日.
- 末永大輝 (口頭発表), 「有限密度 2 カラー QCD における線形シグマ模型の構築とその応用」, KEK 研究会 「熱場の量子論とその応用」, 東海村 (KEK) & オンライン, 2023 年 8 月 28–30 日.
- 末永大輝 (招待講演), 「2 カラー QCD という仮想世界から探る有限密度系のハドロンの理解」, 多彩なハドロンの存在形態を探る理論と実験の最近の発展, 和光市 (理化学研究所), 2023 年 9 月 2 日.
- 末永大輝 (口頭発表), 「ハドロンの有効理論を用いた音速ピーク構造の再現: 有限密度系 2 カラーカイラル有効理論による平均場解析」, ～中性子星の観測と理論～研究活性化ワークショップ 2023, 京都市 (京都大学), 2023 年 9 月 6–8 日.
- 末永大輝 (口頭発表), “Probing the hadron mass spectrum in two-color dense QCD with the linear sigma model,” ELPH 研究会 C035 「実験, 反応・構造計算, 格子 QCD で解き明かすハドロン分光」, 仙台市 (東北大学), 2023 年 11 月 8–9 日.

吉田大輔 (口頭発表), 高木牧人, 北幸海, 島崎智実, 立川仁典, 「グリシン分子の陽電子束縛における立体構造の影響」, 日本コンピュータ化学会 2023 年秋季大会, 高松市 (レグザムホール), 2023 年 11 月 24–26 日.

吉田大輔 (口頭発表), 高橋開人, 「 $\text{Ni} + \text{CO} \rightarrow \text{NiCO}$ のスピントロニクスオーバー反応の正しい理解」, 第 25 回理論化学討論会, 横浜市 (資生堂 S/PARK ホール), 2023 年 5 月 16–19 日.

[Seminars]

P. Naidon (invited), “Halo Universality and the Efimov effect in three-body systems,” Berlin (Freie Universität Berlin), Germany, July 18, 2023.

A. J. Arifi, “Heavy meson in light-front quark model,” Khon Kaen (Khon Kaen University), Thailand, February 28, 2024.

A. J. Arifi, “Structure of mesons in light-front quark model,” Nagoya (Nagoya University), Japan, June 23, 2023.

L. Happ, “Few-body systems in one dimension,” 2023 Newcomers Seminar, RIKEN Nishina Center, Wako (RIKEN), Japan, June 13, 2023.

L. Happ, “Dependence of three-body resonance states on dimensionality and mass ratios,” Ulm (Institut für Quantenphysik), Germany, November 3, 2023.

D. Suenaga, 「2 カラー QCD という仮想世界から探る有限密度系のハドロンの理解」, 名古屋市 (名古屋大学), 2023 年 9 月 28 日.

D. Suenaga, “Quark-gluon and hadron dynamics in extreme conditions,” Wuhan (Central China Normal University), China, November 17, 2023.

Press Release

Y. Lyu, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, and J. Meng, 「クォーク 4 個から成る「純粋テトラクォーク」—加速器実験で見た新粒子をスーパーコンピュータ「富岳」で解明—」, https://www.riken.jp/press/2023/20231020_3/index.html. 2023 年 10 月 20 日.

Award

A. J. Arifi, Incentive prize, Strangeness Nuclear Physics (SNP) School, December 15, 2023.

Outreach Activity

吉田大輔, 立川仁典, 「分子クラスターへの陽電子束縛機構に関する理論研究」, 日本陽電子科学会 会誌『陽電子科学』 第 21 号, pp. 19–27 (2023).