Subnuclear System Research Division
Strangeness Nuclear 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
(5) Equation of state for neutron stars

3. Summary of Research Activity

(1) Hypernuclei

We have investigated the role of hyperons in the structure of atomic nuclei. Using the antisymmetrized quasi-cluster model (AQCM), we investigated the role of up to two Λ hyperons in isotopes of Be and C. The presence of the Λ hyperons attract the α clusters to distances where the spin-orbit interaction can break the cluster structure. We found that while the reduction of the cluster structure is significant in C, it remains limited for Be. We have also proposed a new way to study the spin-isospin dependence of the ΞN interaction by adding α particles in order to make a ΞN pair bound without altering its spin-isospin structure. The energy levels were calculated by the Gaussian Expansion Method (GEM) using ab-initio ΞN potentials obtained from lattice QCD calculations. It was found that the pair becomes bound in the presence of two α particles, leading to spin-doublet bound states in both the isospin triplet and singlet channels. The calculation predicts that the spin-doublet energies are inverted when the isospin configuration is changed, revealing the isospin dependence of the ΞN interaction. We proposed to check these predictions in experiments involving K mesons on ^{10}B targets to produce Ξ$N\alpha\alpha$ bound states.

(2) Neutron-rich nuclei

We have investigated the possible exis tence of a ^{7}H resonant state, by modelling this system as an effective ^{3}H-n-n 5-body system solved with the GEM. We found no narrow resonance but a broad structure at $E_R \approx 9$ MeV above this threshold corresponding to the ^{7}H ground state. In a separate work, we have devised a reaction model to describe the fast removal of the α-particle in ^{8}He nucleus leading to the emission of 4 neutrons. Our model explains the energy peak observed in experiment as consequence of dineutron-dineutron correlation rather than the existence of a hypothetical tetraneutron.

(3) Few-body universality

We have investigated the universal geometry of three-body halos made of loosely bound core and two particles, such as two-neutron halo nuclei. This geometry could be calculated analytically. It was found that in absence of resonance between the two particles, the size of the halo increases logarithmically with the inverse of the binding energy, but close to the resonance between the two particles, it becomes proportional to the inverse of the binding energy. These analytical universal properties were also shown to apply to Efimov states that are observable in cold-atom experiments. In a different work, we looked at the specific case of the two-neutron halo of ^{19}B, computing its properties numerically using the GEM and the Faddeev method. These calculations confirmed that its geometrical properties are model-independent.

(4) Exotic hadron systems

We have used chiral effective theories of diquarks and quark-diquark to investigate doubly heavy tetraquarks $Q_{\bar{q}\bar{q}}$ 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.

(5) Equation of state for neutron stars

To obtain the equation of state of neutron stars at the hadron-quark crossover we interpolated the relativistic mean-field (RMF) model and Nambu-Jona-Lasinio (NJL) model with an interpolation method that reduces randomness. In a different work, we also resolved the technical problem of spurious states appearing the numerical solutions of the Dirac equation solved with the finite-difference method.

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List of Publications & Presentations

Publications

[Original Papers]

N. Itagaki and E. Hiyama, "Cluster-shell competition and effect of adding hyperons," Phys. Rev. C **107**, 024309 (2023).

E. Hiyama, M. Isaka, T. Doi, and T. Hatsuda, "Probing the ΞN interaction through inversion of spin-doublets in $\Xi N\alpha\alpha$ nuclei," Phys. Rev. C **106**, 064318 (2022).

E. Hiyama, R. Lazauskas, J. Carbonell, and T. Frederico, "Scaling of the ^{19}B two-neutron halo properties close to unitarity," Phys. Rev. C **106**, 064001(2022).

E. Hiyama, R. Lazauskas, and J. Carbonell, "^{7}H ground state as a ^{3}H + 4n resonance," Phys. Lett. B **833**, 137367 (2022).

S. Choi, E. Hiyama, C. -H. Hyun, and M. -K. Cheoun, "Effects of many-body interactions in hypernuclei with Korea-IBS-Daegu-SKKU functionals," Eur. Phys. J. A **58**, 8 (2022).

T. Yamashita, Y. Kino, E. Hiyama, S. Jonsell, and P. Froelich, "Near-threshold behavior of positronium-antihydrogen scattering cross sections," Phys. Rev. A **105**, 052812 (2022).

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).

Y. Lyu, T. Doi, T. Hatsuda, Y. Ikeda, J. Meng, K. Sasaki, and T. Sugiura, "Attractive N-phi interaction and two-pion tail from lattice QCD near physical point," Phys. Rev. D **106**, 074507 (2022).

Y. Lyu, H. Tong, T. Sugiura, S. Aoki, T. Doi, T. Hatsuda, J. Meng, and T. Miyamoto, "Optimized two-baryon operators in lattice QCD," Phys. Rev. D **105**, 074512 (2022).

P. Naidon, L. Pricoupenko, and C. Schmickler, "Shallow trimers of two identical fermions and one particle in resonant regimes," SciPost Phys. **12**, 185 (2022).

Z. Yang, G. J. Wang, J. J. Wu, M. Oka, and S. L. Zhu, "The investigations of the P-wave B_S states combining quark model and lattice QCD in the coupled channel framework," J. High Energy Phys. **01**, 058-1–19 (2023).

G. J. Wang, Q. Meng, and M. Oka, "The S-wave fully-charmed tetraquark resonant states," Phys. Rev. D **106**, 096005-1–9 (2022).

N. Yamanaka and M. Oka, "Weinberg operator contribution to the CP-odd nuclear force in the quark model," Phys. Rev. D **106**, 075021-1–15 (2022).

Y. Kim, M. Oka, and K. Suzuki, "Doubly heavy tetraquarks in a chiral-diquark picture," Phys. Rev. D **105**, 074021-1–17 (2022).

Y. Kim, M. Oka, D. Suenaga, and K. Suzuki, "Strong decays of singly heavy baryons from a chiral effective theory of diquarks," Phys. Rev. D **107**, 074015 (2023).

D. Suenaga and M. Kitazawa, "Effective model for pure Yang-Mills theory on $T^2 \times R^2$ with Polyakov loops," Phys. Rev. D **107**, 074502 (2023).

D. Suenaga, K. Murakami, E. Itou, and K. Iida, "Probing the hadron mass spectrum in dense two-color QCD with the linear sigma model," Phys. Rev. D **107**, 054001 (2023).

M. Furushima, M. Takagi, D. Yoshida, Y. Kita, T. Shimazaki, and M. Tachikawa, "Theoretical investigations of positron affinities and their structure-dependent properties of carbon dioxide clusters $(CO_2)_n$ (n = 1–5)," Phys. Chem. Chem. Phys. **25**, 625 (2022).

D. Yoshida, Y. Kita, T. Shimazaki, and M. Tachikawa, "A comprehensive theoretical study of positron binding and annihilation properties of hydrogen bonded binary molecular clusters," Phys. Chem. Chem. Phys. **24**, 26898 (2022).

[Proceedings]

T. Yamashita, E. Hiyama, K. Piszczatowski, S. Jonsell, and P. Froelich, "A four-body calculation of s-wave resonant scattering between positronium and antihydrogen atom," JJAP Conf. Proc. **9**, 011002 (2023).

T. Doi, Y. Lyu, H. Tong, T. Sugiura, S. Aoki, T. Hatsuda, J. Meng, and T. Miyamoto, "Finite volume analysis on systematics of the derivative expansion in HAL QCD method," PoS LATTICE **2021**, 564 (2022).

Y. Lyu, H. Tong, T. Sugiura, S. Aoki, T. Doi, T. Hatsuda, J. Meng, and T. Miyamoto, "Most charming dibaryon near unitarity," PoS LATTICE **2021**, 606 (2022).

T. Sugiura, Y. Akahoshi, T. Aoyama, T. M. Doi, and T. Doi, "Nuclear force with LapH smearing," PoS LATTICE **2021**, 565 (2022).

Y. Akahoshi, S. Aoki, and T. Doi, "Emergence of the rho resonance from the HAL QCD potential," PoS LATTICE **2021**, 625 (2022).

Y. Kamiya, K. Sasaki, T. Fukui, T. Hyodo, K. Morita, K. Ogata, A. Ohnishi, and T. Hatsuda, "Femtoscopic study on the ΛΛ-NΞ interaction," Supl. Rev. Mex. Fis. **3**, 0308124 (2022).

A. Ohnishi, Y. Kamiya, K. Sasaki, T. Fukui, T. Hyodo, K. Morita, K. Ogata, and T. Hatsuda, "Femtoscopic study of coupled-channel baryon-baryon interactions with $S = -2$," Proc. Sci. **380**, 212 (2022).

K. Murakami, D. Suenaga, E. Itou, and K. Iida, "Measurement of hadron masses in 2-color finite density QCD," PoS LATTICE **2022**, 154 (2023).

D. Suenaga, "Roper-like singly heavy baryons in a chiral model," Rev. Mex. Fis. Suppl. **3**, 0308025 (2022).

Presentations

[International Conferences/Workshops]

E. Hiyama (invited), "Structure of light Ξ hypernuclei and ΞN interaction," 66th OMEG-SSANP Workshop, Seoul, Korea, February 22, 2023.

E. Hiyama (invited), "Structure of heavy hydrogen nucleus, ^{7}H with t + 4n cluster model," Fudan Frontiers of Nuclear Physics Open Forum, Online, January 11, 2023.

E. Hiyama (invited), "Structure of Ξ hypernuclei and ΞN interaction," EMMI Workshop "Meson and Hyperon Interactions with Nuclei" Kitzbühel, Austria, September 14–16, 2022.

E. Hiyama (invited), "The resonance of ^{7}H with t + 4n model," Nuclear Physics at the Edge of Stability, Trento Italy, July 4–8, 2022.

E. Hiyama (invited), "Structure of light Ξ hypernuclei," 14th International Conference on Hypernuclear and Strange Particle Physics (HYP2022), Prague, Czech Republic & Online, June 27–July 1, 2022.

T. Doi and G. Mantzaridis (invited), "$p\Omega$ and ΛΞ: experimental and theoretical overview," workshop on Femtoscopy in high-energy collisions at ALICE (FemTUM 2022), Munich, Germany & Online, August 31–September 2, 2022.

T. Doi for HAL QCD Collaboration (invited), "Nuclear physics from lattice QCD," 15th Asia Pacific Physics Conference (APPC15), Seoul, Korea & Online, August 21–26, 2022.

T. Doi for HAL QCD Collaboration (invited), "Lattice QCD study of hadron interactions with strangeness," 14th International Conference on Hypernuclear and Strange Particle Physics (HYP2022), Prague, Czech & Online, June 27–July 1, 2022.

P. Naidon (invited), "Universal geometry of Borromean halo states," The 3rd Japan-France Workshop "Few-body problems in Physics—From atoms to quarks," Tohoku University, Sendai, Japan, February 27–March 3, 2023.

P. Naidon (invited), "Few- and many-body physics of mass-imbalanced two-component systems," Lecture at the programme "Living Near Unitarity," Kavli Institute for Theoretical Physics, UC Santa Barbara, Santa Barbara, U. S. A, May 12, 2022.

M. Oka, "Chiral effective theory of diquarks and application to heavy hadron spectrum," 14th International Conference on Hypernuclear and Strange Particle Physics (HYP2022), Prague, Czech Republic & Online, June 27–July 1, 2022.

T. Fukui (oral), "Shell model study of chiral three-nucleon force," Physics of RI: Recent Progress and Perspectives, RIKEN, Wako, Japan, May 31–June 1, 2022.

T. Fukui (oral), "Shell model study of chiral three-nucleon force," Developments of Physics of Unstable Nuclei (YKIS2022b), YITP, Kyoto University, Kyoto, Japan, May 9 –June 17, 2022.

D. Suenaga (oral), "Modifications of diquark masses at finite density," 3rd J-PARC HEF-ex WS, Tokai, Japan, March 14–16, 2023.

D. Suenaga (oral), "Phase structure of pure Yang-Mills theory in an anisotropic system: A new extreme condition of QCD" The 9th International Conference on Quarks and Nuclear Physics, Online, September 5–9, 2022.

D. Suenaga (oral), "Phase structure of pure Yang-Mills theory in an anisotropic system: A new extreme condition of QCD," The XVth Quark Confinement and the Hadron Spectrum Conference, University of Stavanger, Stavanger, Norway, August 1–6, 2022.

L. Happ (invited), "Universal effects in one dimension," The 3rd Japan-France Workshop "Few-body problems in Physics—From atoms to quarks," Sendai, Japan, February 27–March 3, 2023.

[Domestic Conferences/Workshops]

肥山詠美子 (招待講演), 「少数多体系物理からみたハイパー核の現在と将来」, 「ハイパー核研究の進展と未来〜格致日新〜」, 仙台市 (東北大学), 2022 年 12 月 17 日.

肥山詠美子 (口頭発表), 「クラスター観点からみた軽い中性子過剰原子核とハイパー核の構造」, 大阪公立大研究会「原子核におけるクラスター物理の新展」, 大阪市 (大阪公立大学), 2022 年 10 月 19–20 日.

土井琢身 for HAL QCD collaboration (口頭発表), 「物理点 QCD 配位におけるバリオン間相互作用 (Strangeness = −4, 0) 」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.

P. Naido (invited), "Mass-imbalanced two-component system," 基研・iTHEMS 国内モレキュール型研究会 2022 「少数系の量子ダイナミクス」, 京都市 (京都大学基礎物理学研究所), 2022 年 8 月 22 日–26 日.

P. Naidon (invited), "Efimov physics and low-energy universality in few-body systems," The YONUPA Summer School, Online, August 7–9, 2022.

岡眞, "Fully-charmed tetraquark and quark confinement," ELPH 研究会 C033「ハドロン分光に迫る反応と構造の物理」, 仙台市 (ELPH), 2022 年 12 月 6–7 日.

M. Oka, D. Jido, G. J. Wang, 「マルチクォーク系のクォーク閉込めポテンシャル」, 日本物理学会 2022 年秋季大会, 岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

福井徳朗（口頭発表）, 「カイラル相互作用による軽い核のクラスター構造の理解に向けて」, 大阪公立大研究会「原子核におけるクラスター物理の新展開」, 大阪市 (大阪公立大学), 2022 年 10 月 19–20 日.

T. Fukui (oral), L. Coraggio, G. De Gregorio, A. Gargano, N. Itaco, 「カイラル 3 体力のテンソル構造と軽い核のスピン軌道分離」, 日本物理学会 2022 年秋季大会, 岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

末永大輝 (口頭発表), "Mass modifications of diquarks in medium from chiral symmetry and anomaly," J-PARC ハドロン研究会 2023, オンライン, 2023 年 3 月 27–29 日.

末永大輝 (口頭発表), 「NJL 模型に基づいた有限密度系のダイクォークの性質変化」, 日本物理学会 2023 年春季大会, オンライン, 2023 年 3 月 22–25 日.

末永大輝 (口頭発表), "Modifications of diquark masses at finite density with chiral symmetry restoration," RCNP workshop on Hadron Physics at the LEPS2 photon beamline, 佐用郡 (SPring-8), 2023 年 3 月 6–7 日.

末永大輝 (招待講演), "Pentaquark picture for singly heavy baryons from chiral symmetry and anomaly," Physics of heavy-quark and exotic hadrons 2023, 那珂郡 (J-PARC), 2023 年 1 月 30–31 日.

末永大輝 (口頭発表), 「カイラル対称性とアノマリーに着目したペンタクォーク的ヘビーバリオンの性質」, ELPH 研究会 C033「ハドロン分光に迫る反応と構造の物理」, 仙台市 (ELPH), 2022 年 12 月 6–7 日.

末永大輝 (基調講演), 「非等方空間における pure Yang-Mills 理論の相構造: QCD の新しい極限環境としての非等方系」, 熱場の量子論 2022, 京都市 (京都大学基礎物理学研究所), 2022 年 9 月 20–22 日.

末永大輝 (口頭発表), 「線形シグマ模型を用いた 2 カラー QCD 物質中のハドロン質量変化」, 日本物理学会 2022 年秋季大会, 岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

末永大輝 (口頭発表), 「QCD の新しい極限環境としての非等方ユークリッド空間」, 日本物理学会 2022 年秋季大会, 岡山市 (岡山理科大学), 2022 年 9 月 6–8 日.

伊藤駿平, 吉田大輔, 北幸海, 島崎智実, 立川仁典 (口頭発表), 「量子モンテカルロ法を用いた分子ジアニオンの陽電子束縛に関する理論研究」, 第 16 回分子科学討論会, 横浜市 (慶應義塾大学), 2022 年 9 月 19–22 日.

伊藤駿平, 吉田大輔, 北幸海, 島崎智実, 立川仁典 (口頭発表), 「アニオン 2 量体の陽電子化合物に対する量子モンテカルロ法を用

いた第一原理理論研究」, 日本物理学会 2022 年秋季大会, 目黒区 (東京工業大学), 2022 年 9 月 12–15 日.

吉田大輔, 北幸海, 島崎智実, 立川仁典 (口頭発表), 「2 成分水素結合クラスターにおける陽電子束縛及び対消滅機構に関する理論研究」, 第 24 回理論化学討論会, 金沢市 (金沢商工会議所), 2022 年 5 月 17–20 日.

L. Happ (invited), "Universality in one-dimensional quantum three-body systems," Mini-workshop on ultracold-atom theory, Wako-shi, Japan, November 22, 2022.

[Seminars]

T. Doi, "Hybrid quantum annealing via molecular dynamics," Seminar at RIKEN R-CCS, Online, Wako, Japan, June 14, 2022.

T. Doi, "Nuclear physics from lattice QCD," Seminar at KMI Colloquium, Online, Nagoya University, Nagoya, Japan, June 8, 2022.

P. Naidon (invited), "Universal few-body clusters of heavy and light particles," seminar at Institut Pluridisciplinaire Hubert Curien, CNRS/Université de Strasbourg, Strasbourg, France, December 13, 2022.

P. Naidon (invited), "Miscibility and Polaron physics in two-component BEC," Seminar at CESQ, Université de Strasbourg, Strasbourg, France, December 7, 2022.

P. Naidon, "Mass-imbalanced two-component system," "Mini-workshop on ultracold-atom theory," RIKEN, Wako, Japan, November 22, 2022.

T. Fukui, "Theoretical study of three-nucleon force," GPPU Seminar, Graduate Program on Physics for the Universe, Tohoku University, Sendai, Japan, July 15, 2022.

D. Suenaga, "Heavy-quark spin polarization induced by the Kondo effect in a magnetic field," QCD theory seminar, Online, January 16, 2023.

末永大輝, "Continuous transformation from hadrons to quarks in medium by means of a quark model," 文京区 (東京大学), 2022 年 11 月 11 日.

D. Suenaga, "Singly heavy baryons from chiral symmetry," Asia Pacific Center for Theoretical Physics, Korea, June 23, 2022.

末永大輝, "Heavy-quark spin polarization induced by the Kondo effect in a magnetic field," 京都市 (京都大学基礎物理学研究所), 2022 年 6 月 3 日.

末永大輝, "Singly heavy baryons from chiral symmetry," 目黒区 (東京工業大学), 2022 年 5 月 16 日.

Award

T. Fukui, Presentation Award of FY2022 SPDR Presentation of Research Results, RIKEN, January 18, 2023.

Others

P. Naidon: Chairman at the International Symposium on Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2022), Sendai International Center, Sendai, October 31–November 3, 2022.

T. Fukui: RIKEN Wako Open Campus 2022, RIKEN, Saitama, Japan, April 23, 2022.