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A Focused Review of the Ali-Bodmer Potential: A Phenomenological Model for Alpha-Alpha and Exotic Cluster Interactions

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Abstract

The intricate tapestry of the universe is woven from the interplay of elementary particles and the fundamental forces governing their interactions. Phenomena at all scales, from the subatomic realm of quarks and leptons to the grand structures of galaxies, are ultimately manifestations of these interactions. While the Standard Model of particle physics offers a robust framework for describing the most basic processes, the pathways from these elementary interactions to the emergence of stable nuclei, complex elements, and ultimately, life, remains a profound and unresolved challenge. Pivotal to bridging this gap is the development of effective theoretical models that can accurately characterize the forces between composite particles, such as atomic nuclei, which are themselves complex, many-body quantum systems. This paper rigorously examines the Ali-Bodmer potential—a seminal, phenomenological model introduced in 1965 to describe the interaction between alpha particles. By systematically analyzing its mathematical structure and success in reproducing experimental scattering data, we elucidate the model's central role as a "folding model," which conceptually simplifies complex many-body interactions into a more tractable two-body potential. The enduring impact of the Ali-Bodmer potential is further highlighted through its diverse applications in the study of nuclear systems and astrophysical processes, such as the triple-alpha process responsible for forging carbon in stars. By tracing the legacy of this foundational model, we connect the historical evolution of theoretical nuclear physics to contemporary frontiers in quantum science, demonstrating the profound and far-reaching consequences of elementary particle interactions, from the formation of matter to the very principles of quantum entanglement that underpin the rapidly developing field of quantum computing.

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Introduction

The quest to understand the fundamental building blocks of the universe and the forces that govern their behavior has been a central pillar of physics for centuries. From the subatomic realm of quarks and leptons to the macroscopic scales of galaxies and cosmic structures, all phenomena are ultimately manifestations of elementary particle interactions. While the Standard Model of particle physics provides a comprehensive framework for describing these interactions, the intricate dynamics of how these forces give rise to stable matter, complex elements, and ultimately, life, remains a frontier of discovery. A crucial step in this journey involves developing effective models to describe the forces between composite particles, such as atomic nuclei, which are themselves aggregates of elementary particles. The universe is created from the interactions of elementary (or quantum) particles. A basic understanding of the matter-forming interactions of the elementary particles and life-forming interactions of the elements are still far from being understood.

The Challenge of Describing Composite Particle Interactions

The intricate architecture of matter, from the simplest nuclei to the grandest galaxies, is ultimately a product of interactions between elementary particles. While the Standard Model of particle physics offers a robust framework for describing the most fundamental forces, a profound challenge arises when we move beyond the most basic constituents to consider composite particles, such as atomic nuclei. These systems are complex, multi-body quantum entities, and a direct calculation of the forces between them is computationally intractable. For example, describing the interaction between two alpha particles—each composed of two protons and two neutrons—would require a massive, many-body calculation involving all eight constituent nucleons and their quantum properties. The sheer complexity of such a task underscores the need for effective, simplified theoretical models that can accurately characterize the forces between these composite systems.

The Ali-Bodmer Potential as a Solution

Pivotal to bridging this gap is the development of a framework that can "fold" the complex, underlying many-body interactions into a more manageable two-body potential. This paper rigorously examines the Ali-Bodmer potential, a seminal phenomenological model introduced in 1965 to describe the interaction between alpha particles. By systematically analyzing its mathematical structure and its success in reproducing experimental scattering data, we elucidate the model's central role as a "folding model." The Ali-Bodmer potential, in its simplest form is represented by an attractive Gaussian force:

$$V_{\alpha\alpha}(r) = -V_0 exp\left(-\frac{r^2}{r_0^2}\right), \quad (1)$$

conceptually simplifies the complex interplay of many-body interactions into a tractable two-body potential, capturing the essential features of the strong nuclear force at both short and long ranges. This powerful simplification allows for the exploration of nuclear phenomena that would otherwise be computationally inaccessible.

Equation (1) describes only a purely attractive Gaussian force. It represents a highly simplified concept of the attractive nuclear force component in a folding model. Critically, it lacks the essential repulsive core and the Coulomb interaction. Because the repulsive component is indispensable for reproducing experimental phase shifts and satisfying the requirements of the Pauli principle, Equation (1) is fundamentally inadequate as a definition of the Ali–Bodmer potential. Therefore, it is explicitly identified as a rudimentary conceptual framework. The standard, correct phenomenological definition used by Ali and Bodmer (1966) to fit scattering data:

$$V_{\alpha\alpha}(r) = V_R e^{-(\beta_R r)^2} - V_A e^{-(\beta_A r)^2} + V_C(r) \tag{2}$$

where, $V_R e^{-(\beta_R r)^2}$ is the repulsive term, which models the Pauli exclusion principle at very short distances between the two alpha particles, $V_A e^{-(\beta_A r)^2}$ is the attractive term, which represents the strong nuclear force at intermediate distances, and $V_C(r)$ is the Coulomb term, representing the electrostatic repulsion between the two positively charged alpha particles. This three-term structure is necessary to capture all physical features: short-range repulsion V_R, intermediate-range attraction V_A, and long-range Coulomb repulsion V_C. See later for more on parameters explanation.

An Enduring Impact: Applications and a Cohesive Research Timeline

The enduring impact of the Ali-Bodmer potential is further highlighted by its widespread and diverse applications over the decades. Initially, the model's primary success was in reproducing the elastic scattering data for alpha-alpha interactions (Ali & Bodmer, 1965) [1]. However, its utility quickly expanded to address a variety of more complex nuclear phenomena. This paper examines the significant influence of the Ali-Bodmer potential and the folding model [1], that established an innovative approach for calculating interactions between composite particles, specifically the α−α force field. By reviewing the various applications of this model over the years, its lasting importance in nuclear physics is demonstrated. By examining the legacy of this model through its diverse applications over several decades, one can appreciate its enduring relevance in elementary particle physics. We will then expand our focus from these microscopic interactions to a broader cosmological and biological context, exploring how these fundamental forces lay the groundwork for the formation of the universe and the emergence of life. Finally, we will connect these historical and physical foundations to a modern and rapidly evolving field—quantum computing—by examining the role of quantum entanglement, a direct and startling consequence of the very quantum-level interactions that the Ali-Bodmer model sought to describe.

Background and Rationale

In the decades that followed, researchers utilized the Ali-Bodmer potential to gain a deeper understanding of nuclear structure. The Ali-Bodmer potential (aka, force field) model is an early example that was worked out in 1965 [1] which was the first of its kind to explain the interactions between certain elementary particles. Subsequently, the Ali-Bodmer model was applied to solve the binding energy problem of many elementary interactions such as the α−α interaction, Ξ-nucleon interaction, and others. The strength of the model was realized via many applications including a 3α system [2], the Ξ-nucleon interaction [3], bonding potential between two ^{12}C nuclei [4], The Quantum Liquid of Alpha Clusters—A Variational Approach [5], bare α−α potential and implications on α-matter properties [6], the Four-body extension of the continuum-discretized coupled-channels method [7], two- and three-alpha systems with nonlocal potential [8], the adiabatic solution of the few-body integrodifferential equation [9] and others (e.g., Funaki, et al. [10]), and wave function of ^{9}Be in the three-body (ααn)-model [11]. The model's influence also extends into the realm of nuclear astrophysics. Ultimately, fundamental interactions lead to the formation of different matters and further interaction of matters (elements) lead to the creation of life. The vastness of the various kinds of interactions and the resulting systems require millions of volumes to describe, which are filling up the libraries around the world. The Ali-Bodmer potential has been critical in providing the theoretical basis for understanding the triple-alpha process [6], the stellar fusion reaction by which three alpha particles are converted into a carbon nucleus. This reaction is fundamental to stellar evolution, and the Ali-Bodmer potential provides a key tool for calculating the reaction rates that govern the formation of carbon in the cosmos. In essence, by simplifying the intractable many-body problem, the Ali-Bodmer potential has been instrumental in bridging the gap from the subatomic realm to the grand structures of the universe.

Another interesting consequence of the interactions is the quantum entanglement that forms the basis of quantum computing. Quantum entanglement is a fundamental quantum mechanical phenomenon wherein the quantum states of two or more particles become intrinsically linked, such that the state of each particle cannot be described independently of the states of the others, regardless of the spatial separation between them. This profound interconnectedness, arising from particle generation, mutual interaction, or shared spatial history, defies classical intuitions and has far-reaching implications for both the foundations of physics and the development of quantum technologies. The topic of quantum entanglement is at the heart of the disparity between classical and quantum physics. Accurate identification of quantum entanglement is fundamental to quantum computing, where, unlike the binary states used in classical computing, a vast spectrum of states can exist between 0 and 1. This paper sheds light on such vastness of the universe forming interactions, starting from the folding model calculation of a two-body system and expanding it towards the understanding of many-body system.

The Ali-Bodmer Potential: A Foundational Model

In the mid-20th century, physicists were grappling with the problem of describing the strong nuclear force, particularly as it pertained to interactions between clusters of nucleons, such as alpha particles. An alpha particle, composed of two protons and two neutrons, is an exceptionally stable and compact nuclear cluster. Understanding the force between two alpha particles is fundamental to describing the structure of many light nuclei, most notably the beryllium and carbon isotopes.

The Ali-Bodmer (AB) potential, first proposed by S. Ali and A. R. Bodmer in 1965, offered a breakthrough in this area. It is a "folding model" potential, a concept that conceptually simplifies the problem by treating the interaction between two composite particles as a "folded" sum of the individual nucleon-nucleon interactions within them. Instead of trying to calculate the complex interplay of all individual protons and neutrons across the two clusters, the folding model provided an effective, two-body potential that accurately reproduced the experimental data for the α−α scattering phase shifts. This approach was a significant advancement, as it captured the essential physics of the strong interaction between these complex particles without the computational complexity of a full many-body calculation. The success of this model was not merely its accuracy but its elegance, providing a physically intuitive and mathematically tractable framework that became a cornerstone for future research. As indicated before, the AB potential is a two-body potential, a phenomenological key model for the interaction between alpha particles. As shown in Eq. (2), it is composed of three terms: a short-range repulsive Gaussian term, a longer-range attractive Gaussian term, and a Coulomb term. Clark and Krotscheck [12] have shown that the repulsive strengths V_R found in the original, L-dependent AB parameterizations is ≈ 475 MeV. For the Gaussian exponents. For the Gaussian exponents $e^{-(\beta_R r)^2}$, standard practice dictates that the range parameters $\beta_R = 0.8\, fm^{-1}$). The authors indicate that the repulsive strength of the AB interaction drops from 475 MeV for $L = 0$, to 320 MeV for $L = 2$, to10 MeV for $L = 4$ [12]. In their calculation of α-matter properties, they used only the L = 0 component of this interaction, acting in all states. Although this simplification overestimates the binding energy somewhat, the authors postulate that use of the more attractive L-dependent interaction would only lead to more binding and could lead to the behavior of the model being even less realistic with respect to stability.

With the potential (Eq. (2)) defined for the α-α interaction, the AB folding model can be solved for the α-α binding energy. The AB folding model, when applied within the framework of the Resonating Group Method (RGM), leads to a specific integro-differential equation. The RGM is a microscopic, first-principles approach that describes the interaction between composite particles, like alpha-particles, by considering the antisymmetrization of all the constituent nucleons. The general form of the RGM equation for a two-cluster system is given by:

$$\langle \Phi_{\alpha\alpha} | H - E | \mathcal{A}\{\Phi_\alpha(1)\Phi_\alpha(2)u(r)\}\rangle = 0 \tag{3}$$

Where: $\Phi_{\alpha\alpha}$ is the total wave function for the two-alpha system, H is the many-body Hamiltonian of the system, E is the total energy, $\mathcal{A}$ is the antisymmetrization operator, which ensures that the total wave function is properly antisymmetric with respect to the exchange of all nucleons, $\Phi_\alpha(1)$ and $\Phi_\alpha(2)$ are the internal wave functions of the two alpha-clusters, and *u(r)* is the unknown function of the relative separation coordinate r between the two alpha-clusters, which is the function to solve for. After performing the antisymmetrization and integrating over the internal coordinates of the alpha-clusters, this equation simplifies into the following integro-differential equation for the relative motion wave function *u(r)*:

$$[T_r + V_D(r) + V_C(r) - E_{rel}]u(r) + \int K(r, r')u(r')dr' = 0, \tag{4}$$

where, T_r is the kinetic energy operator for the relative motion, V_D *(r)* is the direct potential, which corresponds to the folding of the nucleon-nucleon interaction. The Ali-Bodmer potential is a phenomenological representation of this term. V_C *(r)* is the direct Coulomb potential between the two alpha-clusters, E_{rel} is the relative energy of the system, *K(r,r')* is the non-local exchange kernel. This is a crucial term that arises from the antisymmetrization of the nucleons and makes the equation an integro-differential equation. The folding model with the Ali-Bodmer potential provides a local approximation to this full non-local interaction. The term *u(r)* is the radial wave function for the relative motion, and *u(r')* is the same function evaluated at a different position r'. The term $\int K(r,r')u(r')dr'$ represents the non-local part of the interaction, which is a key feature of the RGM. This non-local term accounts for the effects of nucleon exchange between the two clusters.

Applications and Legacy of a Versatile Force Field

The true strength of the Ali-Bodmer model lies in its versatility and the extensive body of work it inspired. Its initial success in explaining the α−α interaction opened the door to a wide range of applications, demonstrating its adaptability to different systems and problems within nuclear physics.

The Three-Alpha System and the Hoyle State: One of the most significant applications was its use in the study of the three-alpha system, which forms the ^{12}C nucleus. The Ali-Bodmer potential was instrumental in explaining the structure and binding energy of this system, particularly the famous Hoyle state—a resonant excited state of ^{12}C that is crucial for the nucleosynthesis of carbon in stars. Cheng-Guang (1982) utilized the force field to investigate the correlations within this 3α system, providing key insights into the structure of this essential element [2].

Beyond Alpha Particles: The model's applicability was not limited to alpha particles. Rahman, Kazi, and Ali (1984) [3] extended the model to study the interaction between a Ξ particle (a strange baryon) and a nucleon. This application highlighted the model's robustness and its ability to adapt to systems involving exotic particles, contributing to our understanding of hypernuclei. Similarly, Sarangi, Ali, and Satpathy (1990) [4] applied a folding model based on the Ali-Bodmer potential to study the bonding between two ^{12}C nuclei, a problem of relevance in nuclear reaction theory.

Modern Reinterpretations and Extensions: Decades after its inception, the Ali-Bodmer potential continues to be a point of reference and a tool for modern theoretical work. Carstoiu and Mişicu (2010, 2011) [5, 6] used the potential as a basis for variational approaches to study alpha clusters and alpha-matter properties. Descouvemont (2018) integrated the model into a four-body extension of the continuum-discretized coupled-channels method, showcasing its relevance in contemporary few-body reaction calculations [7]. More recently, Papp and Moszkowski (2018) employed the potential in their investigation of two- and three-alpha systems with nonlocal potential [8], and Phenyane (2021) and Rakityansky (2024) have used it in their work on few-body equations and the wave function of ^9Be respectively [9, 11]. The model's persistent use over nearly six decades is a testament to its foundational importance and its effectiveness as a reliable tool for understanding nuclear systems.

In summary, the folding model is a theoretical approach used in nuclear physics to calculate the interaction potential between a nucleon or a strange particle (like the Ξ) and a nucleus (like the α particle). This is done by "folding" the interaction between the strange particle and a single nucleon with the matter density distribution of the nucleus. According to theoretical calculations using the folding model [12], the binding energy of the α-Ξ interaction for the $_{\Xi}^{5}H$ hypernucleus, which is a system composed of an α-particle and a Ξ^- particle, is approximately 0.5 MeV. This value is for a resonance state that appears below the $\alpha+\Xi^-$ threshold.

From Elementary Particles to the Universe and Life

The journey from the Ali-Bodmer potential to the existence of the universe and life itself is a profound one. The forces that this model describes are the very same forces that governed the earliest moments of cosmic evolution. In the heart of stars, hydrogen and helium nuclei are fused together through nuclear reactions, creating heavier elements. The formation of carbon, for example, is a direct result of the triple-alpha process, where three alpha particles fuse to form a ^{12}C nucleus. The interactions within this 3α system, as studied using the Ali-Bodmer potential, are therefore inextricably linked to the creation of an element that is the cornerstone of life as we know it.

As stars live and die, they forge a diverse array of elements and scatter them across the cosmos. These elements then interact through chemical forces, leading to the formation of molecules, minerals, and eventually, the complex organic compounds that form the basis of biological systems. Thus, the fundamental interactions of elementary particles, which are the subject of theoretical models like the Ali-Bodmer potential, are not merely abstract concepts; they are the genesis of all matters and, by extension, the source of life's intricate complexity. The universe is a vast tapestry woven from these fundamental forces, and every atom in our bodies is a product of these elementary interactions.

Quantum Entanglement and the Dawn of Quantum Computing

A fascinating and non-intuitive consequence of quantum mechanical interactions is the phenomenon of quantum entanglement. As described in the abstract, this occurs when two or more particles become linked in such a way that their quantum states are interdependent, regardless of the physical distance separating them. The measurement of one particle's state instantaneously determines the state of the other, a correlation that bewildered even Albert Einstein, who famously referred to it as "spooky action at a distance."

The profound implications of entanglement have recently moved from theoretical physics to a practical application in the field of quantum computing. Unlike classical computers, which use binary bits to represent information as either 0 or 1, quantum computers use qubits. A qubit can exist in a superposition of both 0 and 1 simultaneously, enabling it to perform multiple calculations at once. However, the true power of a quantum computer comes from entanglement. By entangling qubits, their states are linked, allowing them to cooperate to perform complex calculations in parallel. This exponentially increases the computational power of the system, offering the potential to solve problems that are currently intractable for even the most powerful supercomputers, such as factoring large numbers, simulating complex molecular systems, and optimizing logistics. The Ali-Bodmer potential represents a historical effort to understand the forces of the quantum world, while quantum computing represents the modern effort to harness the most bizarre and powerful consequences of that same world.

From Folding Models to Quantum Computing

The journey from the Ali-Bodmer potential to quantum computing is not a linear path but a profound conceptual loop that connects a classical problem in nuclear physics to a modern solution in computational science. The central challenge addressed by the Ali-Bodmer potential—the many-body problem—is also one of the primary drivers behind the development of quantum computing.

At its core, the Ali-Bodmer model is an elegant approximation. It simplifies the highly complex, many-body interaction of the protons and neutrons within two alpha particles into a single, manageable two-body potential. This "folding" of a vast number of quantum interactions into a simple potential was a necessary and powerful computational shortcut in the pre-quantum computing era. It allowed physicists to successfully model nuclear structures and reactions that were otherwise impossible to calculate. This pragmatic approach, however, left the full quantum mechanical complexity of the system unexamined.This is where the intellectual circle is completed. The very systems that the Ali-Bodmer potential was designed to approximate—complex, interacting quantum systems—are precisely what quantum computers are being built to simulate and analyze. A quantum computer, by leveraging principles such as superposition and entanglement, can handle the exponential growth in complexity that overwhelms classical computers. A qubit, unlike a classical bit, can exist in multiple states at once, allowing a quantum computer to explore a vast number of possibilities simultaneously.

In theory, a sufficiently powerful quantum computer could perform the full, un-approximated many-body calculation that the Ali-Bodmer potential was created to circumvent. It could simulate the complex interactions of all eight nucleons in a two-alpha system, providing a complete picture of the wave function and the resulting forces. Thus, the Ali-Bodmer potential represents the ingenious classical solution to an intractable quantum problem, while quantum computing offers the potential for the ultimate quantum solution to that very same problem. This fascinating transition from a brilliant simplification to a direct simulation highlights the enduring quest to understand the fundamental forces that shape our universe.

Practical Example of Computation of Binding Energy of Ξ-neutron Interaction

The Folding Model for Ξ-Neutron Binding Energy

As described herein, the folding model is a method to simplify the complex, many-body interactions of a system into a more manageable two-body potential. For example, to compute the binding energy for the Ξ-neutron (Ξ-n) interaction, one would follow these key steps:

Define the Ξ-Nucleon Potential ($V_{\Xi N}$)

First, one needs to define the fundamental interaction between a Ξ particle and a single nucleon (a proton or a neutron). This potential, similar to the original alpha-alpha potential described by Ali-Bodmer [1], is typically a phenomenological, two-body potential derived from theoretical or experimental data. Faisal Etminan [12] pointed out that using "state-of-the-art Ξ-N interactions," a common approach is to use a potential with a short-range repulsive core and a longer-range attractive part.

Define the Nucleus's Matter Density (ρA(r))

Next, one needs to characterize the target nucleus, which in this case is a neutron. However, the folding model is most effective when applied to an interaction between a particle (like the Ξ) and a composite nucleus, which has a spatial density distribution. The Ξ-neutron interaction in the context of the Ξ-hypernucleus ${}_{\Xi}^{5}H$ [12] suggests that the model is folding the Ξ-nucleon interaction with the density of the alpha particle (composed of two protons and two neutrons). In this specific scenario, the folding is not with a single neutron but with the alpha particle's density to get a Ξ-alpha potential.

Note that if one were to apply the folding model to a system like the Ξ particle interacting with a single neutron, the concept of "folding" with a density distribution becomes trivial, as a neutron is an elementary particle in this context. The binding energy calculation would then rely on solving the Schrödinger equation with just the two-body Ξ-neutron potential.

Perform the Folding Integral

The core of the folding model is this integral. The potential for the total system, in this case, the Ξ-alpha potential ($V_{\Xi\alpha}$), is calculated by integrating the Ξ-nucleon potential over the matter density distribution of the alpha nucleus. The integral takes the following form:

$$V_{\Xi\alpha}(r) = \int V_{\Xi N}(r' - r)\rho\alpha(r')d^3(r'). \tag{5}$$

Here, r is the separation distance between the Ξ particle and the center of the alpha nucleus, and ρα(r^') is the density of the alpha particle.

Solve the Schrödinger Equation for Binding Energy

Once the folded potential ($V_{\Xi\alpha}(r)$) is obtained, it is used in the Schrödinger equation for the two-body system (Ξ + alpha particle) to find the binding energy:

$$-2\mu\hbar^2\nabla^2\Psi(r) + V_{\Xi\alpha}(r) = E\Psi(r) \tag{6}$$

Where, μ is the reduced mass of the Ξ-alpha system, Ψ(r) is the wave function of the system, and E is the energy, and the binding energy is the magnitude of the negative energy eigenvalue for the bound state. The results for the ${}_{\Xi}^{5}H$ hypernucleus (a system of a Ξ particle and an alpha particle), the binding energy is approximately 0.5 MeV, a value consistent with this folding model approach [12, 13].

Conclusions

The story of the Ali-Bodmer potential is not only a tale of remarkable theoretical achievement but also a profound bridge between the quantum realm and the very fabric of existence. The Ali-Bodmer folding model, in particular, has become a cornerstone in unraveling the intricate interactions that govern the formation of atomic nuclei. Notably, this model has enabled precise calculations, such as determining the binding energy for the interaction between an alpha particle and a Ξ particle in a hypernucleus—estimated to be approximately 0.5 MeV for the resonance state below the $\alpha+\Xi^-$ threshold. This value underscores the subtle yet significant energy scales at which these fundamental processes occur. Through such insights, the model provides a lucid framework for understanding how clusters of alpha particles interact and coalesce, ultimately influencing the pathways by which elements are forged in the hearts of stars.

Its reach extends far beyond the confines of traditional nuclear physics. Through the lens of the folding model, we can trace the delicate choreography that leads to the formation of carbon—a vital element for life—via the triple-alpha process in stellar interiors. By accurately describing the forces and correlations within multi-alpha systems, the Ali-Bodmer model has illuminated the mechanisms by which the universe manufactures the chemical ingredients essential for life. Each insight gained at the quantum level reverberates outward, connecting the synthesis of elements to the emergence of complex molecules, planetary systems, and, finally, living organisms.

In a broader sense, the Ali-Bodmer approach exemplifies how foundational theoretical models can ripple across scientific disciplines and epochs. Its influence is felt in astrophysics, cosmology, and even in the philosophical contemplation of our origins. The model's elegance and adaptability underscore the unity of the physical laws that tie together the smallest building blocks with the grand architecture of galaxies and the emergence of consciousness itself.

As we continue to push the boundaries of quantum theory—venturing into fields such as quantum computing and beyond—the legacy of the Ali-Bodmer folding model persists. It is a reminder that the quest to understand elementary interactions is, at its heart, a quest to understand ourselves and our place in the cosmos. The folding model's capacity to illuminate the path from the first atomic bonds to the spark of life stands as a testament to the enduring power of human curiosity and the intricate beauty of the universe we inhabit.

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions and Dedication

While Professor Ali and Anis Rahman started contemplating this project in early 2023 and a draft framework was established by October of 2024, Professor Ali passed away on August 2, 2025. However, he was active as an academician and as a resercher until his last day. Subsequently, Anis Rahman has conceptualized and written the manuscript, and Abubokor Hanip has reviewed it. Both Anis Rahman and Abubokor Hanip wish to dedicate this paper to the memory of Professor M. Shamsher Ali with profound respect and admiration for his lifelong struggle for cultivating knowledge and instilling a positive outlook into the numerous students he mentored during his lifetime.

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References

1. S Ali and A R Bodmer (1966) "Phenomenological α-α Potentials," Nucl. Phys. 80: 99.
2. B. Cheng-Guang, 1982 (1982) "CORRELATIONS AND STRUCTURE OF A 3a SYSTEM WITH THE ALI-BODMER FORCE," Nuclear Physics 373: 1-12.
3. Anis Rahman, Amin H Kazi and M Shamsher Ali (1984) Bangladesh Atomic Energy Commission Annual Report.
4. P Sarangi, S Ali and L Satpathy (1990) "Bonding potential between two 12C nuclei," Pramina- J. Phys 34: 111-115.
5. F Carstoiu and Ş Mişicu (2010) "The Quantum Liquid of Alpha Clusters, A Variational Approach," AIP Conference Proceedings 1304: 144.
6. F Carstoiu, Ş Mişicu and M Rizea (2011) "BARE α−α POTENTIAL AND IMPLICATIONS ON α-MATTER PROPERTIES," International Journal of Modern Physics E 20: 4.
7. P Descouvemont (2018) "Four-body extension of the continuum-discretized coupled-channels method," PHYSICAL REVIEW C 97: 064607.
8. Z Papp and S Moszkowski (2018) "Two- and three-alpha systems with nonlocal potential," Modern Physics Letters B.
9. R R Phenyane (2021) "THE ADIABATIC SOLUTION OF THE FEW-BODY INTEGRODIFFERENTIAL EQUATION," Dissertation 2021, UNIVERSITY OF SOUTH AFRICA.
10. Y Funaki, H Horiuchi, G Ropke, P Schuck, A Tohsaki and T Yamada (2008) "Density-induced suppression of the α-particle condensate in nuclear matter and the structure of α-cluster states in nuclei," PHYSICAL REVIEW C 77: 064312.
11. S A Rakityansky (2024) "Wave function of 9Be in the three-body (ααn)-model," Phys. Rev. C 110: 024001.
12. J W Clark and E. Krotscheck (2023) "Alpha Matter Revisited,".
13. Faisal Etminan (2024) "$^{5}_{\Xi}$H hypernuclei by folding the state-of-the-art Ξ-N interactions," RIKEN-iTHEMS-Report-23.