Thermodynamic Insights into Symmetry Breaking

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Symmetry breaking is a phenomenon that is observed in various contexts, from the early universe to complex organisms, and it is considered a key puzzle in understanding the emergence of life. The importance of this phenomenon is underscored by the prevalence of enantiomeric amino acids and proteins. The presence of enantiomeric amino acids and proteins highlights its critical role. However, the origin of symmetry breaking has yet to be comprehensively explained, particularly from an energetic standpoint. Therefore, a novel approach is explored by considering energy dissipation, specifically the lost free energy, as a crucial factor in elucidating symmetry breaking.

A comprehensive thermodynamic analysis applicable to all scales from elementary particles to aggregate structures such as crystals is performed, we present experimental evidence establishing a direct link between nonequilibrium free energy and energy dissipation during the formation of the structures. Results emphasize the pivotal role of energy dissipation, not only as an outcome but as the trigger for symmetry breaking. This insight suggests that understanding the origins of complex systems, from cells to living beings and the universe itself, requires a lens focused on nonequilibrium processes

Keywords: energy dissipation ; entropy production ; matter aggregation ; mesostructures ; self-assembly ; self-organization ; symmetry breaking

1. Introduction

Symmetry breaking stands as a foundational concept that extends beyond subatomic and quantum scales, finding applications across diverse scientific disciplines. In particle physics, it sheds light on the origin of mass and particle formation [1][2], while in condensed matter physics, it elucidates material behavior and phase transitions [3][4]. In cosmology, symmetry breaking contributes to understanding the distribution of matter and the formation of large-scale structures in the universe [5]. Additionally, in biology, symmetry breaking plays a fundamental role in embryonic development, giving rise to complex and asymmetric structures [6][7][8]. This versatile concept serves as a unifying principle, connecting phenomena from the subatomic to the cosmic and from the quantum to the classical, highlighting its significance in explaining the emergence of patterns, structures, and asymmetry in the natural world.

At subatomic scales, fundamental forces orchestrate a symmetrical dance among particles. However, this balance is disrupted as specific particles gain mass through the Higgs mechanism, marking a subtle yet profound form of symmetry breaking in the subatomic domain [9]. At the molecular scale, the realm of chirality and enantiomerism illustrates symmetry breaking in biomolecular structures. The prevalence of specific handedness in biological molecules, such as amino acids and DNA, underscores the fundamental role of asymmetry in the foundations of life. Unraveling the origin of this chiral bias remains an intriguing puzzle, interwoven with inquiries into the prebiotic conditions that shaped the essential building blocks of life [10].

Ascending to larger scales, the process of crystal formation stands as a macroscopic manifestation of symmetry breaking. As atoms intricately organize into structured arrays, the resulting crystalline structures showcase distinctive symmetries that diverge from the theoretically perfect arrangement dictated by fundamental atomic interactions. This departure accentuates the influence of diverse factors, encompassing temperature gradients, pressure variations, and the presence of impurities, all of which collectively contribute to shaping the ultimate symmetry exhibited by these materials [11].

Transcending the limits of the molecular and atomic domains, the impact of symmetry breaking resonates across astrophysical scales. The very fabric of the universe carries the echoes of symmetry-breaking occurrences during its early stages. With the formation of galaxies, stars, and planets, the once uniform nature of the cosmos transforms into a complex tapestry of structures, eloquently mirroring the indelible imprint left by primordial asymmetries [5].

Delving into the phenomenon of symmetry breaking across diverse scales and scientific domains holds the promise of unraveling fundamental principles that govern our surroundings and shed light on the origins of the cosmos and life itself. Fluctuations and symmetry breaking, deeply embedded since the inception of space and time, emerge as a recurring theme with profound consequences. Central to this exploration is the phenomenon of energy dissipation through entropy production, which serves to illuminate the complexities of symmetry breaking.

2. Symmetry Breaking

Symmetry breaking is a phenomenon in which the symmetry of a system is lost or altered, leading to the emergence of a preferred state or configuration. This can occur spontaneously when the system transitions from a symmetric to a nonsymmetric state without external influence, or it can be induced by external factors, such as temperature changes or external fields [12][13]. Symmetry breaking plays a crucial role in a variety of natural phenomena, including phase transitions, the formation of patterns and structures, and the emergence of complexity in systems ranging from particle physics to biology [14].

Symmetry breaking manifests itself through various mechanisms, including spontaneous, explicit, and fluctuation-induced processes, as discussed in this review [13]. Spontaneous symmetry breaking occurs when the lowest energy state of a system has a symmetry different from that of the equations governing the system. A common example is symmetry breaking in the phase transition of a material, such as the solid-to-liquid phase transition or in the chiral symmetry breaking of organic molecules. When a term in the system description lacks invariance under symmetry-preserving transformations, it leads to explicit symmetry breaking. For example, the application of an external field can break the symmetry that existed in the absence of such a field. Symmetry breaking induced by thermal or quantum fluctuations can amplify small asymmetries in the system, leading to the selection of a particular state.

In particle physics, spontaneous symmetry breaking by the Higgs mechanism elucidates particle mass generation [15]. Quantum systems exhibit explicit symmetry breaking in Bose-Einstein condensates, revealing superfluidity [16]. Active matter systems display fluctuation-induced symmetry breaking, which drives emergent behaviors in self-propelled particles [17]. At the molecular scale, molecular chirality reflects spontaneous symmetry breaking [18]. Crystalline materials undergo explicit symmetry breaking at phase transitions, giving rise to ordered structures [4]. In biology, fluctuation-induced symmetry breaking drives developmental processes, shaping the asymmetry of the organism and determining cell fate [8].

In symmetry-breaking processes, fluctuations emerge as a fundamental aspect shaping the behavior of systems at all scales [19]. At the mesoscale, thermal fluctuations can trigger spontaneous symmetry-breaking events, leading to the formation of ordered structures such as liquid crystals or magnetic domains. Similarly, in biological systems, fluctuations in molecular concentrations or spatial distribution drive symmetry-breaking processes, influencing cell differentiation and developmental patterns [20]. In addition, fluctuations near critical points during phase transitions can amplify small asymmetries, facilitating the selection of preferred states and altering the symmetry of the system [21]. Quantum fluctuations also contribute significantly to symmetry breaking, playing a crucial role in various quantum mechanical phenomena, such as phase transitions and spontaneous symmetry breaking [22].

3. Conclusions

A fundamental proposition has emerged on the importance of energy dissipation in elucidating symmetry breaking. Energy dissipation through entropy production has emerged as a coherent and compelling phenomenon, which influences the free energy of the system and leads to the establishment of an effective free energy potential. This concept has been thoroughly explored at various scales, from elementary particles to aggregate matter systems such as crystals.

In essence, this discussion delves into the coherence of symmetry-breaking phenomena across different scales and disciplines, revealing a common thread in the dissipation of energy. From the cosmic to the molecular scale, the exploration of this relationship provides valuable insights into the fundamental principles governing the emergence of asymmetry in the physical universe.

References

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