Energy Confinement Theory: Thermodynamic Mechanism of Chiral Selection and a New Hypothesis for the Origin of Life

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Abstract: The long-standing puzzles of chiral selection and the origin of life stem from the failure of classical chemical thermodynamics to achieve intrinsic unification with mass–energy conservation. Based on the law of energy conservation, Einstein's mass–energy equation, and an extension of Newton's first law to chemistry, this study proposes the **Energy Confinement Theory**, which redefines a chemical reaction as a process in which, driven by external energy, molecules maximize energy confinement through conformational optimization. The core equation $E_{input} = \Delta_r U_m^{\theta,*} + W + Q$ reduces mass defect to changes in "confinement energy," achieving compatibility between thermodynamics and mass–energy conservation. Through combustion enthalpy measurements on enantiomers, polymers, and peptide bond formation, combined with multi-dimensional spectroscopic characterizations, the theory experimentally validates that: (i) molecular configuration determines energy confinement efficiency; (ii) the essence of a chemical reaction is conformational optimization and energy confinement driven by external energy; (iii) thermodynamic and kinetic advantages are unified under the criterion of maximizing energy confinement efficiency, $\Delta\Delta_r G_m^{\theta} < 0$. The theory successfully explains the thermodynamic essence of D- sugar enrichment, near- racemic distribution of D/L- amino acids, and the L- amino acid preference in meteoritic peptides, revealing the ultimate reason why living systems select L- amino acids and D- sugars – to maximize the confinement of solar energy. Accordingly, the **Energy Confinement Hypothesis for the origin of life** is proposed: the origin and evolution of life are the inevitable consequence of matter, driven by a continuous flow of energy,

progressively optimizing molecular configurations to enhance energy storage efficiency.

Keywords: Energy Confinement Theory; chemical thermodynamics; confinement energy; chiral selection; origin of life

Introduction

Exploring the widespread homochirality in biomolecules – the selective emergence of L- amino acids and D- sugars – is considered a key clue to unraveling the mystery of the origin of life. Although theories of asymmetric breaking provide some explanation for the initial selection of chiral molecules[1], they cannot account for the cross- scale homochiral consistency between interstellar meteorites and terrestrial life[2]. Recent studies have shown that biopolymers possess a significant energy storage advantage over their racemic counterparts[3], suggesting that thermodynamic driving forces may play a decisive role in molecular evolution. Nevertheless, the mechanism of chiral selection remains unresolved, and the fundamental reason is that the traditional chemical thermodynamics framework has not achieved intrinsic unification with the law of mass–energy conservation.

The cornerstone of modern chemical thermodynamics – the Gibbs free energy criterion ($\Delta G < 0$) – has been the gold standard for judging reaction direction and extent since its establishment in the 19th century. However, this framework, originally derived from physical processes, faces fundamental challenges when explaining chemical phenomena. Why do D- glucose and L- glucose, with identical masses, differ in their heat of combustion by as much as 833.4 kJ/mol? This phenomenon directly challenges the fundamental assumption of classical thermodynamics that enantiomers have identical thermodynamic properties in an achiral environment[5]. This assumption originates from the idea that intermolecular interaction energies depend only on interatomic distances and bond angles, and that mirror- image configurations cannot be distinguished in an achiral environment[6]. However, the measured thermal effects of D- glucose and L- glucose are 3913.9 kJ/mol and 3080.5 kJ/mol, respectively – a difference far beyond experimental error. This difference has been systematically

confirmed by XPS, NMR, and TG, ruling out measurement errors or sample contamination. This implies that the classical thermodynamic assumption of identical thermodynamic properties for enantiomers is not a universal truth, but rather overlooks the fundamental impact of changes in electron cloud spatial distribution caused by molecular configurational differences on energy storage efficiency. Furthermore, endothermic reactions such as photosynthesis and peptide bond synthesis occur widely in nature but are classified as "non-spontaneous" by classical theory. More seriously, classical thermodynamics was developed before Einstein's mass–energy equation ($E = mc^2$), and its concept of "exothermic reaction" implicitly harbors the logical contradiction of mass non-conservation.

Faced with the sharp conflict between theory and experiment, we return to the origin of energy conservation and propose the **Energy Confinement Theory**. This theory holds that a chemical reaction is not a release of energy, but rather a process in which, driven by external energy, molecules achieve maximal confinement of solar radiation energy through conformational optimization. This paper reinterprets chemical reactions from a microscopic perspective, constructs a new framework of chemical thermodynamics that is compatible with mass–energy conservation and can unify endothermic and exothermic processes as well as thermodynamics and kinetics, and accordingly proposes a new hypothesis on the origin of life.

1. Theoretical Limitations of Classical Chemical Thermodynamics and Anomalous Experimental Evidence

In the 19th century, Gibbs proposed the free energy criterion ($\Delta G < 0$), which became the standard for judging reaction spontaneity. However, this framework, derived from physical processes, has systematic limitations when explaining chemical reactions: (i) many clearly endothermic reactions have been confirmed to proceed spontaneously[6], conflicting with the notion that "spontaneity requires heat release"; (ii) non-volume work is tacitly assumed to be zero, ignoring other forms of energy conversion such as electrical work; (iii) the standard enthalpy of formation of elements is defined as zero, neglecting the intrinsic energy revealed by the mass–energy equation. More seriously, if forward and reverse reactions reach

dynamic equilibrium under the same conditions, they would simultaneously satisfy both forward and reverse spontaneity, violating the unidirectional constraint of the second law of thermodynamics[7].

The conflict between theory and assumptions is even more starkly reflected in a series of anomalous experimental data (Table 1 and Table S1):

① **Equal mass but unequal combustion enthalpy:** D-glucose and L-glucose have the same mass, yet their combustion enthalpies differ by 833.4 kJ/mol (3913.9 vs. 3080.5 kJ/mol). XPS, NMR, and TG systematically confirm this difference (Figs. S2–S5), directly challenging the classical assumption that enantiomers have identical thermodynamic properties in an achiral environment.

② **Smaller mass but higher combustion enthalpy:** Ethyl acetate has a lower mass than the sum of acetic acid and ethanol, yet its combustion enthalpy is 12.9 kJ/mol higher; the combustion enthalpy of glycyl-glutamic acid dipeptide is 317.1 kJ/mol higher than the sum of its monomers. These phenomena cannot be explained by traditional mass conservation but directly imply an equivalent conversion between mass and energy in chemical changes.

③ **Polymerization-degree dependence of combustion enthalpy:** The combustion enthalpy of polyethylene glycol (PEG) increases with degree of polymerization (PEG-6000 is 387 J/g higher than PEG-2000); linear starch is 508 J/g higher than β-cyclodextrin.

The above systematic contradiction between theory and experiment indicates that classical thermodynamics fails to incorporate the intrinsic relationship between mass, energy, and molecular configuration, and therefore cannot reasonably explain the changes in energy storage efficiency caused by configurational differences. This urgently calls for a new thermodynamic framework that is intrinsically compatible with mass–energy conservation and can uniformly explain endothermicity, exothermicity, and chiral differences.

Table 1 Determination of Heat of Combustion of Organic Compounds

	Glucose		Ribose		Glu		Phe		Ala	
$\Delta_cH_m^\theta$(kJ/mol)	D	L	D	L	D	L	D	L	D	L
	3913	3080	2386	2318	1645	1643	4654	4628	2279	2272

	PEG		CD	Starch	Phthalic acid		
$\Delta_cH_m^\theta$(J/g)	*-2000*	*-6000*			*o-*	*m-*	*p-*
	26350	26737	15070	15778	19528	19461	19437

	4-AAP-Sal			Salen		
$\Delta_cH_m^\theta$(J/g)	0℃	30℃	75℃	0℃	30℃	75℃
	26316.5	28669	32032	31942	33256	32441

4-AAP-Sal: N-(4-Aminoantipyrine)-salicylidene; Salen: N,N'-bis(salicylidene)-o-phenylenediamine

2. Energy Confinement Theory: A New Framework for Chemical Thermodynamics Based on Mass–Energy Conservation

To overcome the above limitations, this study proposes the **Energy Confinement Theory** based on the law of energy conservation, Einstein's mass–energy equation, and an extension of Newton's first law to chemistry (without external energy input, no chemical reaction proceeds spontaneously).

2.1 Core Elements

① **Different configurations imply different energy confinement efficiencies.** The essence of atoms forming elements or compounds is a combination to achieve energy confinement; molecular configuration is a key factor determining confinement energy.

② **The essence of a chemical reaction is the process of conformational optimization and energy confinement driven by external energy.** There is no absolute spontaneity in chemical reactions. Their essence is the redistribution of energy through dynamic conformational optimization driven by external energy (E~input~), strictly following the energy conservation equation: $E_{input} = \Delta_r U_m^{\theta,*} + W + Q$.

③ **Thermodynamic driving force and kinetic driving force are unified under the same physical goal – to maximize the confinement of solar radiation energy.** Under specific external energy conditions, a system always tends to choose the reaction path with higher energy confinement efficiency.

2.2 Core Equation of the Energy Confinement Theory: $E_{input} = \Delta_r U_m^{\theta,*} + W + Q$

Based on the Energy Confinement Theory, the essence of a chemical reaction is the conservation and conversion of energy through molecular conformational reorganization and electron cloud redistribution driven by external energy (E~input~). Within the framework of mass–energy conservation, the generalized energy equation for a chemical reaction can be expressed as:

$$E_{input} + \sum[U^* + (hf)^*]_{reactant} = \sum[U^* + (hf)^*]_{product} + W + Q$$

Simplified to: $E_{input} = \Delta_r U_m^{\theta,*} + W + Q$

where E_{inpu} is the external input energy (e.g., light energy, electrical energy, ignition); $(hf)^*$ is the confinement energy of each compound; $\Delta_r U_m^{\theta,*}$ represents the change in internal energy of the system, equal to the difference between the confinement energies of products and reactants. Since the types and numbers of elements are conserved before and after the reaction ($\Delta_r U_m^{\theta,*} = \sum (hf)^*_{product} - \sum (hf)^*_{reactant}$), this change in internal energy is entirely contributed by the change in confinement energy; W represents volume work (negative when volume increases, positive when volume decreases); Q represents the heat exchanged between the system and its surroundings (negative for exothermic, positive for endothermic). In the absence of external energy input ($E_{input} = 0$), the equation naturally reduces to the classical first law of thermodynamics.

2.3 Conceptual Analysis of the Core Equation

To deeply understand the physical meaning of the energy conservation equation $E_{input} = \Delta_r U_m^{\theta,*} + W + Q$, the key concepts are analyzed one by one.

2.3.1 Physical Nature of E~input~: Solar Radiation as the Energy Source of Chemical Reactions

Traditional thermodynamics divides reactions into “spontaneous” and “non- spontaneous” and treats 298 K and standard pressure as a “zero energy input” reference state, ignoring the fact that temperature itself is a form of energy input. Hydrogen and oxygen can coexist stably at room temperature; without ignition or an electric spark (external energy input), no reaction occurs. Calcium carbonate must be heated to about 800 °C to decompose. These phenomena show that “spontaneity” is

not an intrinsic property of a reaction; reactions cannot proceed without external energy input.

Tracing further back, whether environmental heat, lightning, or artificial heating or electrocatalysis, the ultimate source can be attributed to **solar radiation**. Temperature differences on the Earth's surface originate from uneven distribution of solar radiation; fossil fuels, wind energy, and hydropower are essentially different conversion forms of solar energy. Therefore, the occurrence and direction of a chemical reaction depend on the presence and intensity of external energy input, whose ultimate source is solar radiation. This understanding revises the limitations of the traditional "spontaneity" criterion and achieves a reasonable extension of Newton's first law from physics to chemistry: **Without external energy input, no chemical reaction proceeds spontaneously.**

2.3.2 Definition of Confinement Energy: Unification and Deepening with the Mass–Energy Equation

Confinement energy is the core physical quantity of the Energy Confinement Theory, used to quantitatively describe the storage capacity of a molecular configuration for externally input energy. In this study, an isolated single atom is taken as the reference, and its confinement energy is defined as zero. When atoms combine to form a molecule through chemical bonds driven by external energy, confinement energy is generated, and its value reflects the additional energy stored by the molecule compared to its constituent atoms. The absolute energy of a compound consists of two parts: the sum of the absolute internal energies of its atoms ($\sum U^*$) and the total confinement energy of the molecule $(hf)^*$:

$$E = \sum U^* + (hf)^* = mc^2 \quad (\text{对于 } E_{H2O} = 2U^*_H + U^*_O + (hf)^*_{H2O})$$

Einstein's mass–energy equation reveals the static equivalence between mass and energy but does not clarify how mass participates in energy conversion and storage in chemical reactions. The Energy Confinement Theory deepens this equation:

$$\Delta E = \Delta mc^2 = \sum[U^* + (hf)^*]_{product} - \sum[U^* + (hf)^*]_{reactant} = \Delta(hf)^* = \Delta_r U_m^{\theta,*}$$

This equation shows that any mass change (Δm) in a chemical reaction directly corresponds to a change in "confinement energy," which in turn originates from

molecular conformational reorganization. Taking $2H_2 + O_2 \rightarrow 2H_2O$ as an example, the mass of a water molecule is not simply the sum of the masses of hydrogen and oxygen atoms; the difference comes from the energy changes accompanying the reaction. This equation can also be extended to nuclear reactions: in uranium-235 fission, the heavy nucleus configuration is disrupted by neutron bombardment, and confinement energy is released as kinetic energy and radiation; in nuclear fusion, light nuclei combine into a heavy nucleus, confining external energy within the new nucleus. Thus, any mass change is accompanied by conformational reorganization and energy confinement or release, and requires external energy input.

2.3.3 Relationship between Confinement Energy and Bond Energy

Confinement energy and traditional bond energy belong to different conceptual levels. Bond energy falls into the category of reductionism: it precisely corresponds to the energy required to dissociate a specific atom from its molecular potential energy curve from the equilibrium position to infinity, answering "how much energy is needed to break this specific atom?" – its essence reflects the influence of the chemical environment on an atom. Confinement energy falls into the category of holism: it answers "how much energy does this molecule store as a whole?" – how this energy is distributed among chemical bonds is not its concern.

Both are different ways of describing the same energy conservation and conversion mechanism, and unification is theoretically possible. Taking the O_2 molecule as an example, its dissociation process satisfies energy conservation: the laser photon energy equals the sum of the bond energy and the internal and kinetic energies of the product atoms ($h\nu = D_0 + \Delta E_{int} \longrightarrow D_0 = h\nu - \Delta E_{intt}$)[8]. From the perspective of the Energy Confinement Theory, the absolute energy of an O_2 molecule is $2U_O^* + (hf)_{O2}^*$, and when driven by external energy for dissociation, it satisfies $(hf)_{O2}^* = E_{\text{input}} - W - Q$. Comparison shows that $(hf)_{O2}^*$ is approximately equal to the bond energy D_0. In general, the larger the total confinement energy of a molecule, the larger the bond energies of its internal chemical bonds tend to be. The unification of the two helps to understand chemical energy storage at both the global and local levels.

3. Experimental Validation: Multi-dimensional Evidence for the Energy Confinement Theory

We designed and carried out a series of systematic experiments around the three core elements. Model systems including enantiomers, positional isomers, polymers with different degrees of polymerization, and peptide bond formation reactions were selected. Combustion enthalpies were precisely measured and combined with spectroscopic methods such as XPS, NMR, IR, and TG for validation.

3.1 Experimental Evidence for Element ①: Configuration Determines Energy Confinement Efficiency

Compounds with the same atoms but different configurations should have different energy confinement efficiencies. Experiments confirmed that the standard combustion enthalpy of D-glucose (3913.9 kJ/mol) is significantly higher than that of L-glucose (3080.5 kJ/mol), $\Delta\Delta_cH_m^\theta$= 833.4 kJ/mol (Table 1). XPS showed that the binding energies of C and O in D-glucose are generally lower than those in L-glucose (ΔE_C=0.11eV， ΔE_O= 0.07eV, Fig. 1a). ^{13}C-NMR showed a single peak at 92.51 ppm for C1 of D-glucose, while L-glucose gave a split doublet (Figs. 1b and 1c). TG (Fig. 1d) and IR (Fig. S5) further supported this difference. The combustion enthalpies of the phthalic acid isomers (*ortho, meta, para*) also showed a significant gradient (Table 1, *ortho* > *meta* > *para*), with systematic changes in spectroscopic characterizations (Figs. S6–S10). The essence of these phenomena is that different molecular configurations lead to different amounts of "confined" energy within the same chemical bonds, manifesting macroscopically as ordered changes in combustion enthalpy.

3.2 Experimental Evidence for Element ②: Conformational Optimization Enhances Energy Confinement Efficiency

Element ② states that driven by external energy, molecules achieve efficient energy confinement through conformational reorganization. Endothermic reactions in the traditional sense are typical manifestations of this process.

Photosynthesis: The combustion enthalpies of CO_2 and H_2O are zero, while the combustion enthalpy of the product D-glucose is 3913.9 kJ/mol – its energy

necessarily comes from solar energy input. ^{13}C-NMR shows a C1 shift of 92.51 ppm for glucose, with the other carbons in the range 30–80 ppm (Fig. 1b), indicating that conformational optimization efficiently converts light energy into chemical confinement energy.

Peptide bond formation: The combustion enthalpy of Gly-Glu dipeptide is 317.1 kJ/mol higher than the sum of its monomers (Table S1). XPS showed a cooperative decrease in the binding energies of C, N, and O (ΔE_C= -1.01 eV, ΔE_N = -1.67 eV, ΔE_O = -0.2 eV, Fig. 2); NMR showed shifts in carbonyl and proton signals (Figs. S11, S12); IR showed a blue shift of the N-H stretch from 3300 cm^{-1} to 3500 cm^{-1} (Fig. S13). The Ala-Glu system verified similar patterns (Figs. S14–S17).

Polymerization: The combustion enthalpy of PEG-6000 is 387 J/g higher than that of PEG-2000. ^{13}C-NMR showed that ethylene glycol (monomer) gives a single carbon signal at 62.75 ppm, PEG-200 gives signals distributed between 60.79 and 72.22 ppm, while the signals for PEG-6000 tend to converge, indicating increased electron cloud symmetry (Fig. 3). ^{1}H-NMR results were consistent (Fig. S18). The NMR data (Figs. S19, S20) and combustion enthalpy differences (linear starch is 508 J/g higher than β-cyclodextrin, Table 1) further confirmed that increasing the degree of polymerization is a key pathway to enhance energy confinement efficiency.

External energy regulation: The combustion enthalpies of the Schiff base compounds 4-AAP-Sal and Salen synthesized at different temperatures (0, 30, 75 °C) changed significantly. Elemental analysis (Table S2) and spectroscopic characterizations (Figs. S21–S25) confirmed that the products obtained at each temperature were the same compound. Nevertheless, the combustion enthalpy of 4-AAP-Sal increased with temperature, and XPS showed systematic shifts of binding energy peaks (Fig. S26). The combustion enthalpy of Salen showed a non-monotonic trend: it increased from 0 to 30 °C, then decreased from 30 to 75 °C; the XPS peak heights followed the order 30 °C > 75 °C > 0 °C (Fig. S27). IR (Fig. 4) revealed that the phenolic hydroxyl C–O bond (1124 cm^{-1}) vibration was enhanced in the product synthesized at 30 °C, while in the 75 °C product the O–H peak (3417 cm^{-1}) disappeared and the C–O bond returned to the 0 °C level, suggesting that high

temperature induces hydrogen bond breaking, weakening the electron-confining ability. These phenomena directly confirm that the essence of a chemical reaction is an energy confinement process driven by external energy (E_{input}).

Exothermic reactions: Traditional theory defines reactions that release heat as "exothermic" and considers them "spontaneous." However, according to the mass–energy equation $E = mc^2$, energy release must be accompanied by a decrease in mass, leading to the contradiction of element conservation but mass non-conservation. Taking hydrogen combustion $2H_2 + O_2 \rightarrow 2H_2O + Q$ ($Q < 0$) as an example, under the Energy Confinement Theory this reaction strictly obeys mass–energy conservation. Ignoring volume work, the energy equation gives the fundamental reason for exothermicity: $2(hf)^*_{H2O} > 2(hf)^*_{H2} + (hf)^*_{O2}$, i.e., water molecules have a higher energy confinement efficiency than hydrogen and oxygen. Bond energy data support this inequality: the sum of bond energies of the reactants is 1370 kJ/mol (H-H: 436×2, O-O: 498), and that of the products is 1856 kJ/mol (O-H: 464×4), a difference of 486 kJ/mol. Similarly, carbon combustion can be resolved as $(hf)^*_{CO2} > (hf)^*_{O2}$, with a bond energy difference of 1108 kJ/mol.

Thus, any chemical reaction simultaneously involves two parallel processes: endothermic (E_{input}) and exothermic (Q). So-called "exothermicity" is an outward manifestation of the formation of high-confinement-energy products – the system stores more energy in the products in the form of confinement energy, releasing the "excess" as heat. This reinterpretation unifies traditional exothermic and endothermic reactions, eliminates the apparent contradiction between mass–energy conservation and chemical reactions, and reveals the essence of energy conversion and storage.

3.3 Experimental Evidence for Element ③: Maximization of Energy Confinement Efficiency – The Unifying Criterion for Thermodynamics and Kinetics

Traditional chemistry treats thermodynamic driving force and kinetic driving force as independent categories. **Element ③** states that under the constraint of energy conservation, the two are unified under the fundamental principle of "maximizing energy confinement efficiency."

Reinterpretation of Gibbs free energy: Direct calculation of E~input~ in the energy equation is difficult, whereas the calculation of $\Delta_rG_m^\theta$ is well established. Traditional thermodynamics views $\Delta_rG_m^\theta$ as a criterion for the work-performing ability of a system, a criterion derived from physical processes (with non-volume work tacitly assumed to be zero, i.e., $\Delta_rG_m^\theta = 0$). Under the framework of the Energy Confinement Theory, we extend it to apply to chemical reactions (Fig. 5a): $\Delta_rG_m^\theta = -E_{input}$, where $-E_{input}$ represents the efficiency of converting external input energy into confinement energy of the product. The more negative $\Delta_rG_m^\theta$, the higher the energy confinement efficiency, and the greater the potential work-performing ability of the product.

Theoretical hypothesis: As shown in Fig. 5b, two competing pathways correspond to products with different confinement energies. According to $\Delta_rG_m^\theta = -E_{input}$, the pathway with higher energy confinement efficiency corresponds to a more negative $\Delta\boldsymbol{\Delta_rG_m^\theta} = \Delta_rG_{m,1}^\theta - \Delta_rG_{m,2}^\theta$. If $\Delta\Delta_rG_m^\theta < 0$, then pathway 1 is thermodynamically favored (higher yield) and kinetically favored (lower activation barrier, faster rate).

Experimental validation: Using DL-amino acids as a model system, we systematically measured the rates and yields of their reactions with organic compounds (ninhydrin, o-vanillin, 2,4-dinitrofluorobenzene) and metal ions (Fe^{3+}, Cu^{2+}, Ni^{2+}) (Figs. S28–S34, Tables S3–S6). The results showed that when reacting with the same reagent, L-amino acids consistently exhibited higher reaction rates and yields, and their corresponding $\Delta_rG_m^\theta$ values were more negative (Fig. 6), i.e., $\Delta\boldsymbol{\Delta_rG_m^\theta} = \Delta_rG_{m,L}^\theta - \Delta_rG_{m,D}^\theta < 0$, indicating that the reaction pathway involving L-amino acids has a higher energy confinement efficiency.

Combining theoretical derivation and experimental results, we propose a universal reaction-path selection rule: **$\Delta\Delta_rG_{m,D}^\theta < 0$ can serve as a unified criterion for determining the advantage of a reaction pathway** – under the constraint of energy conservation, a chemical reaction always tends to maximize its energy confinement efficiency.

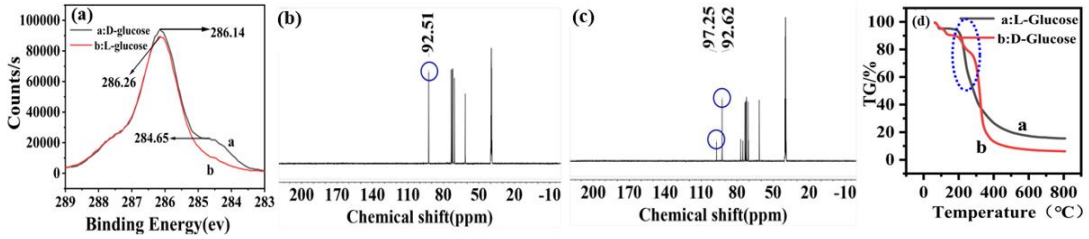

Figure 1 Multi-dimensional characterization of D/L-glucose: (a) XPS, (b) ^{13}C NMR spectrum of D-glucose, (c) ^{13}C NMR spectrum of L-glucose, (d) TG curves

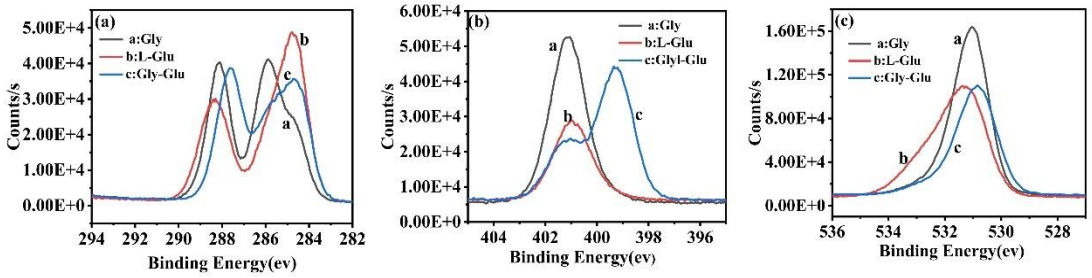

Figure 2 XPS analysis of glycine (Gly), glutamic acid (Glu), and Gly-Glu dipeptide: (a) C 1s, (b) N 1s, (c) O 1s

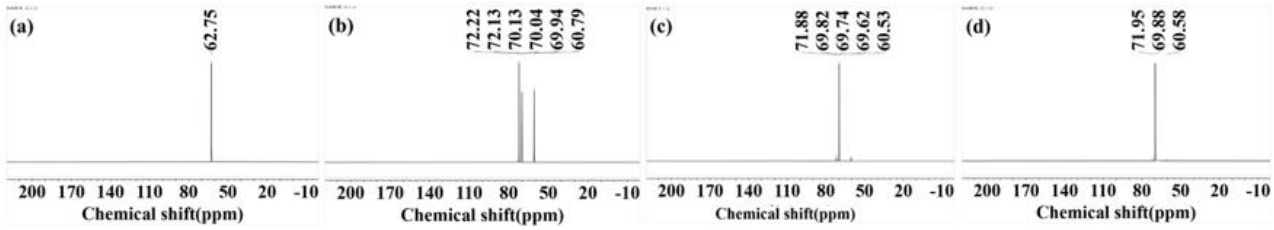

Figure 3 ^{13}C NMR spectra of polyethylene glycols (PEG) with different molecular weights: (a) ethylene glycol (monomer), (b) PEG-200, (c) PEG-2000, (d) PEG-6000

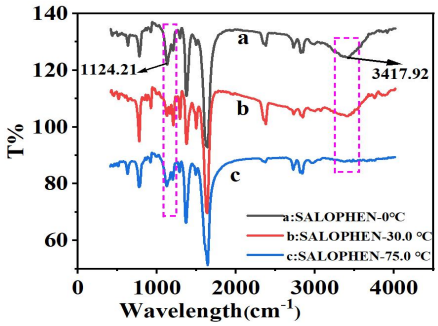

Figure 4 Infrared spectra of Salen synthesized at different temperatures

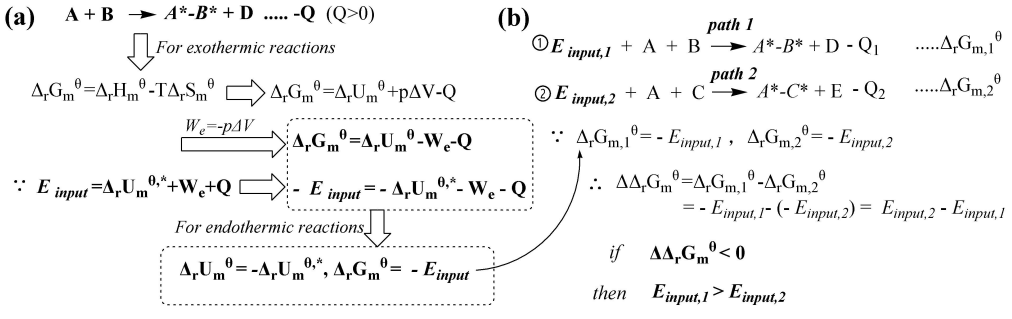

Figure 5 Reconstruction of the thermodynamic system under the Energy Confinement Theory (a: revised $\Delta_rG_m^{\theta}$; b: $\Delta\Delta_rG_m^{\theta}< 0$ as the path selection for maximizing energy confinement)

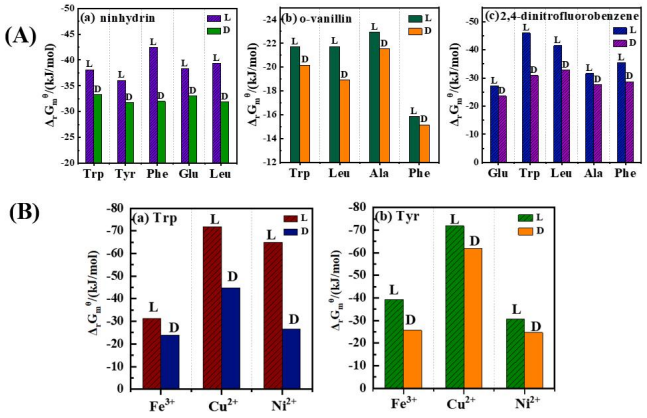

Figure 6 Comparison of $\Delta_rG_m^{\theta}$ for reactions of different substances with DL- amino acids (A: different organic compounds; B: different metal ions)

4. Thermodynamic Analysis and Experimental Support for Chiral Selection Mechanisms

The previous sections have experimentally validated the three core elements of the Energy Confinement Theory. This section applies the theory to the long- standing problem of chiral selection, systematically analyzing the unified thermodynamic mechanisms behind the enrichment of D- sugars and near- racemic distribution of amino acids in meteorites[9], the L- preference of peptides[10], and the homochirality of living systems. It will further demonstrate that the distribution patterns of chiral molecules in meteorites are not random accidents but an inevitable outcome of astrochemical evolution driven by external energy and following the principle of maximizing energy confinement efficiency.

4.1 From cosmic evolution to astrochemistry: a unified perspective of the Energy Confinement Theory

Current cosmic evolution theories, centered on the Big Bang model, have failed to provide a satisfactory explanation for why the temperature of the universe continues to decrease after expansion. The energy equation $E_{input} = \Delta_rU_m^{\theta,*} + W + Q$ proposed in this work offers a self- consistent thermodynamic explanation. In the very early universe, extremely high energy input drove elementary particles to combine into atomic nuclei and atoms, efficiently confining energy in microscopic structures ($\Delta_rU_m^{\theta,*}> 0$). As particles continued to assemble, the environmental heat Q decreased,

leading to a drop in temperature and eventually the formation of celestial bodies. From an astrochemical perspective, cosmic chemical evolution follows a "bottom-up" pathway[11]: elementary particles → atomic nuclei → atoms → simple molecules → complex organic molecules. Each chemical bond is formed when the system, under a specific energy input, optimizes its structure to maximize energy confinement efficiency. Within this framework, the enrichment of D-sugars, the near-racemic distribution of amino acids, and the L-preference of peptide compounds in meteorites are not isolated or accidental phenomena, but rather inevitable consequences of astrochemical evolution strictly obeying the core equation of the Energy Confinement Theory.

4.2 Chiral Distribution of Monomers in Meteorites: D-Sugar Enrichment and Near-Racemic Amino Acids

According to the criterion of maximizing energy confinement efficiency ($\Delta\Delta_rG_m^\theta < 0$), a chemical reaction tends to follow the pathway with higher energy confinement efficiency. The combustion enthalpy of D-glucose (3913.9 kJ/mol) is significantly higher than that of L-glucose (3080.5 kJ/mol), $\Delta\Delta_cH_m^\theta$= +833.4 kJ/mol, indicating that D-glucose has a higher energy confinement efficiency. Therefore, under cosmic energy input, its synthesis pathway is thermodynamically and kinetically favored, leading to the selective enrichment of D-sugars in meteorites. In contrast, D- and L-amino acids have very similar combustion enthalpies (e.g., D-alanine 2279.4 vs. L-alanine 2272.9 kJ/mol), so their energy confinement efficiencies are comparable ($\Delta\Delta_rG_m^\theta \approx 0$), resulting in no significant chiral preference in their synthesis pathways and thus a near-racemic distribution. This contrast directly supports the unified explanation of chiral molecular origins provided by the Energy Confinement Theory.

4.3 L-Amino Acid Preference in Meteoritic Peptides: Evidence for Kinetic Advantage

The condensation of amino acids to form peptide bonds is essentially a process of energy confinement. Since direct determination of $\Delta_rG_m^\theta$ for dipeptide synthesis is difficult, an indirect strategy (Section 3.3) was used: L-amino acids exhibit higher reaction rates and yields than their D-enantiomers when reacting with the same

reagent (Fig. 6), i.e., $\Delta\Delta_rG_m^{\theta} < 0$ (Fig. 5), indicating that L-amino acids have a higher energy confinement efficiency in condensation reactions. This advantage is relatively modest ($\Delta\Delta_rG_m^{\theta} = -7.94 \pm 7.23$ kJ/mol), so under external energy input, although the reaction favors the L-pathway, it is insufficient to drive complete chiral purification. Macroscopically, this results in only a partial L-enantiomeric excess in meteoritic peptides, for example, 16–40% excess for L-glutamic acid and 10–15% excess for L-isovaline in the Murchison meteorite[12].

4.4 Possible Physical Origin of the Kinetic Advantage of L-Amino Acids: The Corotation Effect of Celestial Bodies (Hypothesis)

Does the above kinetic advantage originate from the intrinsic configuration of L-amino acids? Comparative analysis shows that D- and L-glutamic acid and D- and L-alanine have nearly identical combustion enthalpies (Table 1) and highly overlapping NMR spectra (Figs. S35, S36), indicating that the enantiomers themselves have the same energy confinement efficiency and identical physicochemical properties. Therefore, the advantage of L-amino acids in condensation reactions likely comes from the external physical environment. Considering that this selection has persisted for billions of years of Earth's evolution, we propose a hypothesis: **the rotation direction of celestial bodies** may be a universal physical factor driving chiral selection.

In Fischer projection, L-amino acids exhibit a counterclockwise arrangement ($-NH_2 \rightarrow -COOH \rightarrow -R$), consistent with the rotation direction of most celestial bodies in the Solar System and even the Milky Way (west-to-east/counterclockwise). This directional selectivity is also exemplified in macroscopic physics: artificial satellites take advantage of Earth's rotation to save fuel; cyclones in the Northern Hemisphere are all counterclockwise. We speculate that **Coriolis forces** may lower the activation energy of the transition state for condensation reactions of L-type amino acids, thereby increasing the reaction rate and yield, i.e., satisfying $\Delta\Delta_rG_m^{\theta} < 0$. The Coriolis force generated by Earth's rotation, acting continuously in the early environment, may have continuously amplified the condensation advantage of L-amino acids, eventually solidifying into the homochirality of living systems.

It should be emphasized that this is only a hypothesis. At the same time, the Energy Confinement Theory does not reject known factors such as polarized light[13] or mineral catalysis[14], but rather unifies them within the energy equation: polarized light serves as a special form of E_{input}, while mineral catalysis affects the reaction pathway by modulating the rate of change of $\Delta_r U_m^{\theta,*}$. The synergistic action of these factors with the rotation direction of celestial bodies together determines the final distribution of chiral molecules in meteorites and on the early Earth.

4.5 Unified Thermodynamic Explanation of Chiral Selection in Living Systems

The selection of L- amino acids by living systems follows the same principle as the kinetic advantage of L- amino acids observed in meteoritic peptides. As discussed in Section 4.3, the physical origin of this advantage is the synergistic effect between the rotation direction of cosmic celestial bodies and the configuration of L- amino acids. Earth, as an ordinary celestial body, has a rotation direction consistent with that of the vast majority of celestial bodies in the universe; the resulting Coriolis force continuously amplifies the condensation advantage of L- amino acids, eventually solidifying into the homochirality of living systems. This mechanism complements the phenomenon of "homochiral matching enhanced excited- state energy transfer" discovered by Chen et al.[15], together revealing the physical inevitability of biological homochiral selection.

Unlike L- amino acids, the preference of living systems for D- sugars mainly originates from the intrinsic configurational advantage of the sugars themselves. The combustion enthalpy of D- glucose is significantly higher than that of L- glucose (Table 1), indicating that D- glucose has a higher energy confinement efficiency. Thermogravimetric analysis and polymerization experiments (Fig. S37) showed that D- glucose can polymerize at 125 °C, while L- glucose remains stable at this temperature, confirming that D- glucose has both higher thermodynamic and kinetic advantages ($\Delta\Delta_r G_m^{\theta} < 0$). Therefore, the reasons why living systems select D- sugars are twofold: higher energy confinement efficiency (making them the primary energy source) and higher reactivity (providing carbon skeletons for biomolecules).

5. The Energy Confinement Hypothesis for the Origin of Life: From Molecular Conformational Optimization to Enhanced Energy Storage Efficiency

The Energy Confinement Theory provides a new perspective for understanding the origin of life. The Sun radiates approximately 1.49×10^{22} J of energy to Earth every day (1366.1 $W \cdot m^{-2}$), of which about 70% is absorbed[16]. According to the mass–energy equation $E = mc^2$, this corresponds to a daily mass increase of about 116,000 tons. This energy can be converted into "confinement energy" of matter through chemical reactions, driving matter to continuously evolve from small molecules to large molecules.

Based on this, we propose the **Energy Confinement Hypothesis for the origin of life**: the origin and evolution of life, in their physical essence, are the inevitable result of atoms and molecules, driven continuously by external energy (ultimately from the Sun), progressively optimizing their own configurations (e.g., amino acids polymerizing into proteins, nucleotides assembling into DNA) to continuously enhance the efficiency of solar energy confinement. The emergence of characteristic biomolecules such as proteins and DNA is the inevitable consequence of matter, under a continuous flow of energy, undergoing a series of spontaneous but direction- clear conformational optimizations, gradually "learning" how to store energy more efficiently.

This hypothesis echoes Prigogine's dissipative structure theory: a dissipative structure describes how an open system far from equilibrium maintains an ordered structure by dissipating energy[17]; the Energy Confinement Theory reveals that the essence of this "order" is the macroscopic manifestation of energy being efficiently confined within specific molecular configurations. The hypothesis provides testable predictions: if the origin of life is indeed a continuous increase in energy confinement efficiency, then the "primordial soup" on early Earth should contain a series of intermediate molecules whose confinement energy increases stepwise with molecular complexity. This can be tested by synthesis experiments simulating early Earth conditions combined with high- precision combustion enthalpy measurements.

6. Conclusion

The Energy Confinement Theory proposed in this study (core equation $E_{input} = \Delta_r U_m^{\theta,*} + W + Q$) successfully explains, from a thermodynamic perspective, the chiral distribution in meteorites and the homochiral selection in life, and puts forward the Energy Confinement Hypothesis for the origin of life. It should be noted that this work focuses mainly on thermodynamic mechanism analysis; many profound questions remain to be explored, such as: Why do D-sugars have a higher energy confinement efficiency than L-sugars? What is the microscopic mechanism? Why do L-amino acids exhibit a modest kinetic advantage in condensation reactions while their enthalpies of combustion and NMR spectra are nearly identical to those of D-enantiomers? The Energy Confinement Theory provides a unified thermodynamic yardstick for these explorations, but a complete understanding will require further in-depth research.

Note: The experimental methods described in this paper (including detailed procedures, instrument parameters, and raw data for combustion enthalpy measurements, XPS, NMR, IR, TG, etc.) are provided in the Supporting Information.

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