Pauli Exclusion as Finite Address Protection: Collision-Free Fermionic Occupancy, Structural Diversity, and Stable Matter in Finite Distinction Systems

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The Pauli exclusion principle states that no two identical fermions can occupy the same complete quantum state. In standard physics, this is encoded by antisymmetric fermionic wavefunctions and, in relativistic quantum field theory, by the spin-statistics theorem under assumptions such as Lorentz invariance, locality or microcausality, and positive energy. X4 does not replace that theorem. Instead, it gives an FDS interpretation of the operation performed by exclusion: Pauli exclusion is a collision-free occupancy rule for fermionic mode addresses. The central algebra is

$$(a_i^\dagger)^2 = 0, \qquad n_i = a_i^\dagger a_i \in \{0,1\}.$$

This nilpotent occupancy rule does not label identical fermions as classical individuals. It protects address-level occupancy events: a second identical fermionic mode-occupancy event cannot be written into an already occupied address. The result is not merely a microscopic selection rule; it is the address-level foundation for forced structural diversity, atomic shell structure, chemical diversity, degeneracy pressure, and the stability of bulk matter. Bosons are not treated as violations of finite address protection, because multiple occupation of a bosonic mode changes a field-mode amplitude or occupation number rather than creating multiple independently address-protected fermionic occupancy events in the same address. X4 therefore interprets Pauli exclusion as the minimal single-address protection rule for fermionic matter within finite distinction systems, while separating this operational interpretation from the hard QFT spin-statistics theorem and from higher-risk minimality claims about generalized statistics.

Reader contract. X4 is not a replacement for the spin-statistics theorem. It does not derive fermionic antisymmetry from FDS alone, does not claim that bosons violate finite information bounds, and does not claim that Bose-Einstein condensation creates infinite independent distinguishability. The term “token” does not imply classical individuation of identical fermions; it refers to an address-protected occupancy event in a fermionic mode. X4 does not claim all stable structures are caused only by Pauli exclusion, and it does not derive the exact Standard Model fermion content. X4 gives an operational interpretation: Pauli exclusion protects finite fermionic addresses, forces structural diversity, and makes scalable distinction-bearing matter possible.

Claim-status summary

Table I separates standard algebraic facts from FDS interpretations and higher-risk minimality bridges.

Keywords

Finite Distinction Systems; Distinction Theory; Pauli exclusion; fermions; spin-statistics theorem; antisymmetry; fermionic Fock space; nilpotency; address protection; exclusive occupancy; collision-free writing; quantum addresses; structural diversity; stability of matter; degeneracy pressure; atomic shell structure; Bekenstein bound; holography; parastatistics; Bose-Einstein condensation; Physical AI.

INTRODUCTION

Pauli exclusion as structural architecture

The Pauli exclusion principle states that no two identical fermions can occupy the same complete quantum state [6]. In the nonrelativistic wavefunction description this is encoded by antisymmetry:

$$\Psi(\ldots, x_i, \ldots, x_j, \ldots) = -\Psi(\ldots, x_j, \ldots, x_i, \ldots). \tag{1}$$

If two identical fermions attempt to occupy the same state, the wavefunction satisfies $\Psi = -\Psi$, hence $\Psi = 0$. In relativistic quantum field theory the spin-statistics theorem connects half-integer spin with Fermi-Dirac statistics under assumptions such as Lorentz invariance, microcausality, and positive energy [7, 8].

The consequences are architectural. Atoms have shells, chemistry has valence, bulk matter has volume, and compact stars resist gravitational collapse because fermions cannot all fall into the same lowest available mode. X4 asks not whether FDS can replace spin-statistics, but

TABLE I. Central X4 claims, status, and failure or demotion conditions.

Claim	**Status**	**What would weaken or falsify it**
Fermionic creation operators obey nilpotency $(a_i^\dagger)^2 = 0$.	Standard quantum algebra	Identical Standard Model fermions are observed occupying the same complete quantum state.
Pauli exclusion protects single-fermion address occupancy.	FDS interpretation	Fermionic matter remains address-stable and structurally diverse without any single-address occupancy protection.
Exclusion forces structural diversity in fermionic matter.	Physical / operational	Electrons can all occupy the same atomic state while shell structure, valence, chemistry, and matter stability remain unchanged.
Matter stability depends on fermionic antisymmetry.	Standard mathematical physics	Stability of bulk ordinary matter is proven and observed without exclusion-like fermionic antisymmetry or an equivalent mechanism.
Bosonic multiple occupation is not an X4 violation.	Conceptual caveat	Bosonic mode occupation is shown to create multiple independently address-protected fermionic occupancy events at the same address.
$n_i \in \{0,1\}$ is the minimal address-protection rule.	Minimality bridge	Ordinary 3+1-dimensional Standard Model fermions obey generalized finite occupancy $p > 1$, or a lower-overhead alternative to nilpotent fermionic algebra is physically realized.
Degeneracy pressure is macroscopic address protection.	Physical bridge	White-dwarf or neutron-star support occurs without fermionic degeneracy pressure or an equivalent exclusion-like pressure contribution.

what operation the Pauli principle performs in finite distinction systems.

From information explosion to structural diversity

A naive information-density argument would say that if many particles could occupy one state, a finite region could encode infinite information. This statement is too broad. Bosons can occupy the same mode, and a Bose-Einstein condensate does not automatically carry infinite independent distinguishability. Many indistinguishable bosons in one coherent mode are better understood as increased occupation or field amplitude, not as many separately address-protected identity tokens.

The sharper FDS claim is therefore different:

> Pauli exclusion converts address scarcity into structural diversity.

Without fermionic address protection, electrons could collapse into low-lying modes, shell structure would fail, and the diversity needed for chemistry and stable matter would be lost. Pauli exclusion is thus finite address protection: it prevents identical fermionic mode-occupancy events from silently occupying the same quantum address. Address scarcity itself follows from the finite causal reachability boundary analyzed in FDS-P6 [3]: within a finite causal horizon, the number of distinguishable modes any system can resolve is bounded, so exclusive single-address occupancy is the optimal strategy for maximizing structural diversity under that bound.

Contribution

X4 contributes five things. First, it defines quantum addresses and fermionic mode-occupancy tokens inside the FDS vocabulary. Second, it interprets the nilpotency condition $(a_i^\dagger)^2 = 0$ as a one-occupancy-event-per-address collision-free writing rule. Third, it proves a simple address-diversity bound for generalized occupancy cutoffs. Fourth, it gives bosons a positive complementary role as integration, broadcast, and synchronization channels rather than merely treating them as a counterexample. Fifth, it relates the rule to shell structure, bulk matter stability, degeneracy pressure, and Physical AI address-management analogues.

FDS BACKGROUND

Finite distinction systems

An active finite distinction system is represented by

$$\mathcal{S} = (X, E, B, M, Y, A, U, \pi, \ell, \Phi, \mathcal{P}, \tau), \tag{2}$$

where X is internal state, E environment, B boundary, M memory/model state, Y observation channel, A action space, U update rule, π finite projection, ℓ boundary-maintenance loss, Φ resource budget, $\mathcal{P}$ perturbation/pruning family, and τ update timescale [1]. The resource-ledger language is consistent with the finite-cost view of physical operations in information thermodynamics [21]. X4 focuses on the addressability of fermionic matter inside X and M: which physical occupancy events may occupy which quantum addresses without collision.

Quantum addresses

A quantum address is a complete single-particle mode specified by a complete set of compatible quantum labels. For an electron in an atom one may write, schematically,

$$\alpha = (n, \ell, m_\ell, m_s, \ldots), \tag{3}$$

where the ellipsis includes all labels required to individuate the state in the chosen theory. More generally, an address is a single-particle mode i in Fock space.

For fermions,

$$n_i \in \{0, 1\}, \tag{4}$$

whereas for bosons,

$$n_i \in \{0, 1, 2, \ldots\}. \tag{5}$$

The distinction is not that bosons are unconstrained by physics. It is that fermions create address-protected occupancy events, while bosonic modes are field excitations whose multiple occupation does not constitute a collision of identical fermionic addresses. The term “token” below always means a mode-occupancy event, not a classically individuated label attached to one identical particle.

Relation to X3

X3 decomposed the known interactions into operation classes: strong interaction as hadronic/baryonic encapsulation, electromagnetism as connection, weak interaction as identity transformation, and gravity as global causal-geometric / stress-energy accounting [5]. X4 supplies a complementary substrate-level rule: even after hadronic or atomic structures are available, fermionic address protection is required for shell structure, matter stability, and scalable physical memory. Strong encapsulation and Pauli address protection are distinct layers.

STANDARD PHYSICS BASELINE

Fermionic Fock algebra

Fermionic creation and annihilation operators satisfy the canonical anticommutation relations

$$\{a_i, a_j^\dagger\} = \delta_{ij}, \qquad \{a_i^\dagger, a_j^\dagger\} = 0. \tag{6}$$

Setting $i = j$ gives

$$\{a_i^\dagger, a_i^\dagger\} = 2(a_i^\dagger)^2 = 0, \tag{7}$$

so

$$(a_i^\dagger)^2 = 0. \tag{8}$$

The number operator is

$$n_i = a_i^\dagger a_i, \tag{9}$$

and its eigenvalues are 0 and 1. Thus Eq. (8) is the algebraic form of Pauli exclusion.

Spin-statistics theorem

The spin-statistics theorem remains the standard hard theorem connecting half-integer spin to fermionic statistics and integer spin to bosonic statistics [7, 8]. X4 does not replace it. X4 interprets what the resulting fermionic algebra does operationally once it exists: it protects fermionic mode addresses from multiple identical occupancy.

FINITE ADDRESS PROTECTION

Definition 1 (Quantum address)**.** *A quantum address is a complete single-particle mode i specified by the observables and boundary conditions required to individuate a state in the relevant theory.*

Definition 2 (Fermionic mode-occupancy token (identity token))**.** *A fermionic mode-occupancy token (identity token) is an address-protected occupancy event of a fermionic mode. It is not a classically individuated particle label. Its occupancy is protected by nilpotent creation,* $(a_i^\dagger)^2 = 0$.

Definition 3 (Finite address protection)**.** *A system has finite address protection for identical fermionic mode-occupancy tokens if each address supports at most one such occupancy event:*

$$n_i \leq 1. \tag{10}$$

Definition 4 (Structural diversity)**.** *Structural diversity is the forced distribution of fermionic mode-occupancy tokens across distinct addresses rather than collapse into a single low-energy mode. A simple address-diversity count is*

$$D = \sum_i \mathbf{1}[n_i = 1]. \tag{11}$$

Proposition 1 (Pauli exclusion as finite address protection)**.** *For fermionic modes satisfying canonical anticommutation relations, nilpotency* $(a_i^\dagger)^2 = 0$ *implements a one-occupancy-event-per-address rule. This rule is the minimal algebraic form of finite address protection for identical fermionic mode-occupancy tokens in ordinary fermionic Fock space.*

Proof. Canonical anticommutation gives $\{a_i^\dagger, a_i^\dagger\} = 0$, hence $(a_i^\dagger)^2 = 0$. Therefore attempting to create two identical fermions in the same mode gives $(a_i^\dagger)^2|0\rangle = 0$. The allowed occupancy eigenvalues are 0 and 1, so the address is protected against identical double occupancy. ☐

Remark 1 (Collision-free writing, not read-only memory)**.** *The phrase "write protection" is used in a limited sense. It does not mean that a fermionic address is read-only or cannot change through allowed dynamics. It means collision-free writing: a second identical fermionic occupancy event cannot be written into an already occupied address. The Pauli rule prevents overlap-induced identity ambiguity rather than ordinary physical update.*

Proposition 2 (Address diversity bound)**.** *Let $D_p(N)$ be the minimum number of distinct addresses needed to store N identical occupancy events when each address has a maximum occupancy cutoff p. Then*

$$D_p(N) \geq \left\lceil \frac{N}{p} \right\rceil . \tag{12}$$

In the Pauli case $p = 1$, sufficient available addresses imply

$$D_1(N) = N. \tag{13}$$

Thus Pauli exclusion maximizes forced address diversity among finite cutoff rules.

Proof. If each address can hold at most p occupancy events, D addresses can hold at most pD events. To store N events one needs $pD \geq N$, hence $D \geq \lceil N/p \rceil$. For $p = 1$, every event must occupy a distinct address. ☐

BOSONS ARE NOT A COUNTEREXAMPLE

Bosons satisfy

$$[b_i, b_j^\dagger] = \delta_{ij}, \qquad (b_i^\dagger)^N|0\rangle \neq 0, \tag{14}$$

so a bosonic mode may have arbitrary occupation number. This is not a violation of X4 because X4 is about fermionic address-protected occupancy tokens. Multiple bosons in the same mode increase field occupation or coherent amplitude; they do not create multiple individually protected fermionic occupancy events at the same address.

A Bose-Einstein condensate is the clearest caution. It may contain many bosons in one mode while having low configurational diversity. Therefore the central X4 claim cannot be "multiple occupation equals infinite information". The correct claim is narrower:

Fermionic mode addresses require single-occupancy protection.

Bosonic modes play a different architectural role. In the FDS interpretation, fermions implement address-protected differentiation, while bosons implement integration, broadcast, synchronization, and field-mediated coupling between addresses. Fermions protect occupancy identities; bosons enable coherent transmission and shared interaction fields.

WHY $N_{\max} = 1$?

Generalized finite occupancy

The information-density idea alone would not select $N_{\max} = 1$. One could imagine finite alternatives,

$$n_i \in \{0, 1, \ldots, p\}, \tag{15}$$

with $p > 1$, as in generalized or parastatistical settings [9–11, 26]. Recent work shows that non-trivial parastatistics can exist in physical systems and can obey generalized exclusion principles; this is why X4 treats $p = 1$ as an operational minimality bridge for ordinary Standard Model fermions rather than as a denial of all generalized statistics [26]. X4 therefore treats $p = 1$ as a minimality bridge, not as a derivation from FDS alone. FDS explains the operational economy of $p = 1$, not the spin-statistics origin of $p = 1$.

Minimal nilpotent algebra and address cost

For $p = 1$, the nilpotent rule $(a_i^\dagger)^2 = 0$ is the simplest exact occupancy cutoff. For $p > 1$, the theory requires additional internal algebra, sector labels, braid/topological structure, or parastatistical bookkeeping. Such structures may exist in special systems or dimensions, but they are not the ordinary Standard Model fermion rule in $3 + 1$ dimensions.

From an address-accounting perspective, $p > 1$ shifts cost from address expansion to collision resolution. If several occupancy events share one address, a retrieval or interaction protocol must still disambiguate which sub-occupancy, internal index, or parastatistical sector is being addressed. For example, in fractional statistics (anyons), tracking particle-exchange histories requires topological braiding bookkeeping that grows with the number of anyons per mode; this extra complexity is precisely the type of "extra maintenance cost" that FDS predicts for $p > 1$ occupancy rules [11]. A normal-form ambiguity cost is

$$C_{\mathrm{amb}}(N, p) \propto N \log_2 p, \tag{16}$$

for $p > 1$, with $C_{\mathrm{amb}}(N, 1) = 0$. This is not a universal thermodynamic law. It is an audit term expressing that multi-occupancy addresses require extra bookkeeping to remain operationally distinguishable. The Pauli rule $p = 1$ is the zero-collision, zero-ambiguity finite-address rule.

Conjecture 1 (Minimal fermionic address protection)**.** *Among finite occupancy rules for identical fermionic matter in ordinary* $3+1$*-dimensional relativistic QFT, the Pauli rule* $n_i \in \{0,1\}$ *is the minimal address-protection algebra compatible with stable fermionic mode-occupancy tokens.*

Remark 2 (Status)**.** *The standard hard result is spin-statistics. The FDS minimality claim explains why the single-occupancy rule is operationally economical; it does not prove that all mathematically possible generalized statistics are impossible in all dimensions or effective systems [26].*

STABILITY OF ATOMIC MATTER

Pauli exclusion forces electrons into distinct orbitals, producing shell structure and valence. Without exclusion, many electrons could collapse into the lowest available orbital in a simplified model, destroying the differentiated outer-shell structure that underwrites chemical diversity.

This is the central physical reorientation of X4:

$$\boxed{\text{Pauli exclusion forces matter to use address space.}} \tag{17}$$

The periodic table is not just a list of nuclei; it is a consequence of forced address diversity among electrons. Atomic size, valence, bond geometry, and chemical differentiation depend on electrons being distributed across states rather than all occupying one lowest mode.

X4 does not claim that Pauli exclusion alone explains all chemical structure. Electromagnetic interaction, nuclear charge, quantum dynamics, and many-body effects are essential. The claim is that without fermionic address protection the shell architecture required for ordinary chemistry would fail.

STABILITY OF BULK MATTER

Rigorous mathematical physics shows that fermionic antisymmetry is central to the stability of matter. Dyson and Lenard established foundational stability results, and Lieb-Thirring inequalities provide kinetic-energy lower bounds that support extensive energy scaling [12–15]. In simplified terms, stable matter satisfies a bound of the form

$$E(N) \gtrsim -CN, \tag{18}$$

whereas without exclusion-like kinetic pressure collapse-prone models can scale superlinearly.

The FDS interpretation is that extensive stability is scalable memory architecture. A material system whose storage cost or collapse tendency grows too rapidly with token number cannot support macroscopic distinction-bearing structures. Pauli exclusion makes fermionic matter scalable by preventing many identical occupancy events from being stored in the same address and by forcing kinetic pressure when density rises.

DEGENERACY PRESSURE AND COMPACT OBJECTS

Degeneracy pressure is the macroscopic pressure generated by fermionic address protection. For a nonrelativistic ideal Fermi gas,

$$P_{\text{deg}} \propto n^{5/3}, \tag{19}$$

while relativistic scaling tends toward $P \propto n^{4/3}$. This pressure supports white dwarfs against gravity until the Chandrasekhar limit is reached [16]. Neutron degeneracy, nuclear interactions, and general relativity enter neutron-star support up to the Tolman-Oppenheimer-Volkoff regime [17, 18].

X4 does not derive these limits from FDS. It interprets degeneracy pressure as a macroscopic expression of finite fermionic address protection. Gravity supplies the catastrophic fallback when density exceeds global stability conditions; Pauli exclusion supplies the low-energy algebraic protection that allows structured matter to exist before that fallback dominates.

RELATION TO FINITE INFORMATION BOUNDS

Finite regions have finite accessible distinguishability. Bekenstein-type and holographic bounds provide a global consistency background for finite information density [19, 20]. X4 should not be read as claiming that the Bekenstein bound directly proves Pauli exclusion. The more precise relation is:

$$\boxed{\begin{array}{c}\text{Pauli exclusion is locally consistent with finite}\\ \text{addressability.}\end{array}}$$

It prevents fermionic matter from collapsing into address-degenerate low-diversity structures, while gravitational collapse and horizon bounds remain global high-density cutoffs.

RELATION TO NEARBY FDS PAPERS

X4 is the matter-address substrate paper. It complements X3's strong-interaction encapsulation row by

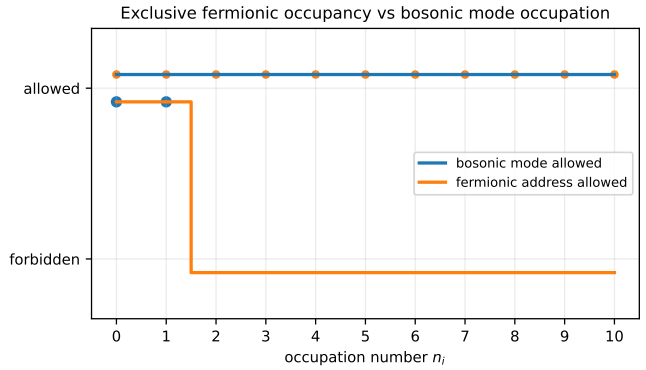

FIG. 1. Fermionic address protection versus bosonic mode occupation. Fermionic addresses allow $n_i = 0$ or 1; bosonic modes allow arbitrary occupation. This is the algebraic distinction underlying X4.

showing how fermionic address protection stabilizes and diversifies matter after encapsulated material tokens exist [5]. It complements P6 because address protection limits how densely identity-bearing occupancy events can be maintained under resource and update constraints [3]. It complements P7 because fermionic address labels are protected algebraically, though not topologically in the same sense as the P7 invariant-ledger examples [4]. It also connects to P4's anti-recurrence theme: once an address is occupied, an attempted identical write is not a reversible overwrite but an algebraically forbidden collision [2].

NUMERICAL AND ALGEBRAIC DEMONSTRATIONS

The figures are deterministic algebraic or normal-form demonstrations generated by `code/generate_results.py`. They are not empirical fits, experimental data, or physical simulations of real atoms or compact stars.

FALSIFICATION AND DEMOTION CONDITIONS

The hard falsification condition is direct observation of two identical Standard Model fermions occupying the same complete quantum state. Experimental searches for Pauli-exclusion violation, including forbidden atomic transitions and spin-statistics tests, probe this class of possibility [22–25]. Modern low-background searches such as Gator at LNGS [23] and independent germanium-detector searches [24] constrain PEP-violating transitions, providing direct experimental tests of the hard X4 falsification channel.

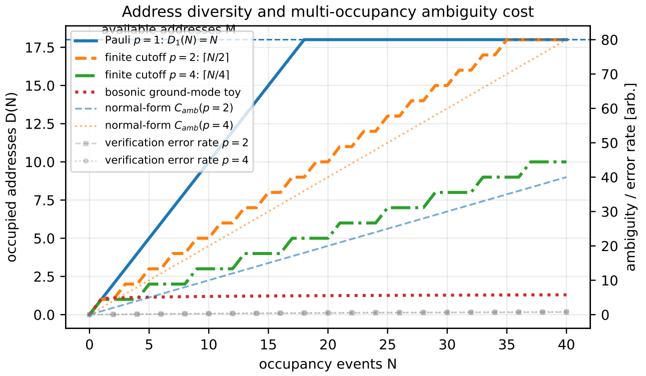

FIG. 2. Address diversity under filling. With Pauli protection, the number of occupied addresses grows with token number until the available address set is full. In an energy-minimizing bosonic-mode toy model, many tokens can remain in one mode. The generalized $p = 2$ and $p = 4$ curves illustrate why $p = 1$ is a minimality bridge rather than a direct consequence of finite capacity alone. The ambiguity-cost and verification-error curves are normal-form bookkeeping terms, not empirical thermodynamic data.

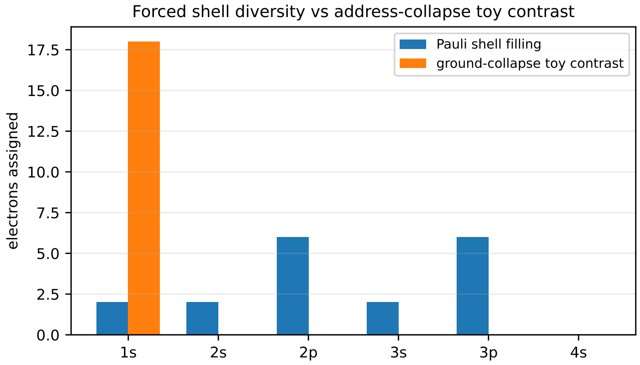

FIG. 3. Shell-filling cartoon. Pauli exclusion forces electrons into multiple shells, creating valence and chemical diversity. The collapse-to-ground curve is a toy contrast for address collapse, not a proposed alternative atomic physics model.

The minimality bridge is demoted if ordinary $3 + 1$-dimensional Standard Model fermions exhibit generalized occupancy $p > 1$. Recent VIP-2 measurements provide stringent constraints on parastatistical Quon-model violations of Pauli exclusion, directly supporting the X4 demotion boundary for generalized occupancy rules [25]. Anyonic and fractional statistics in lower-dimensional effective systems do not automatically falsify X4, because X4 is about ordinary fermionic address protection in the matter substrate of our observed world.

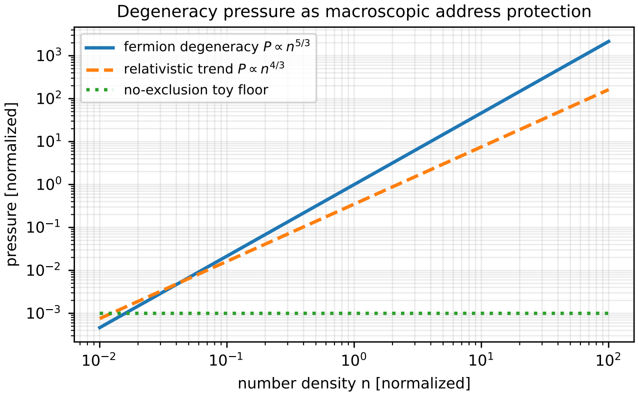

FIG. 4. Degeneracy pressure normal form. Nonrelativistic fermion degeneracy pressure scales as $P \propto n^{5/3}$, with relativistic trends approaching $n^{4/3}$. The figure illustrates address-protection pressure, not a full stellar-structure calculation.

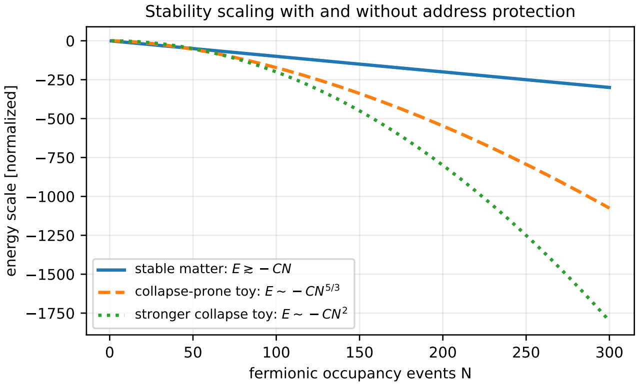

FIG. 5. Normal-form stability scaling. Extensive stability corresponds to an energy lower bound proportional to $-N$, while collapse-prone toy models scale superlinearly. The figure visualizes the FDS interpretation of matter stability as scalable address architecture.

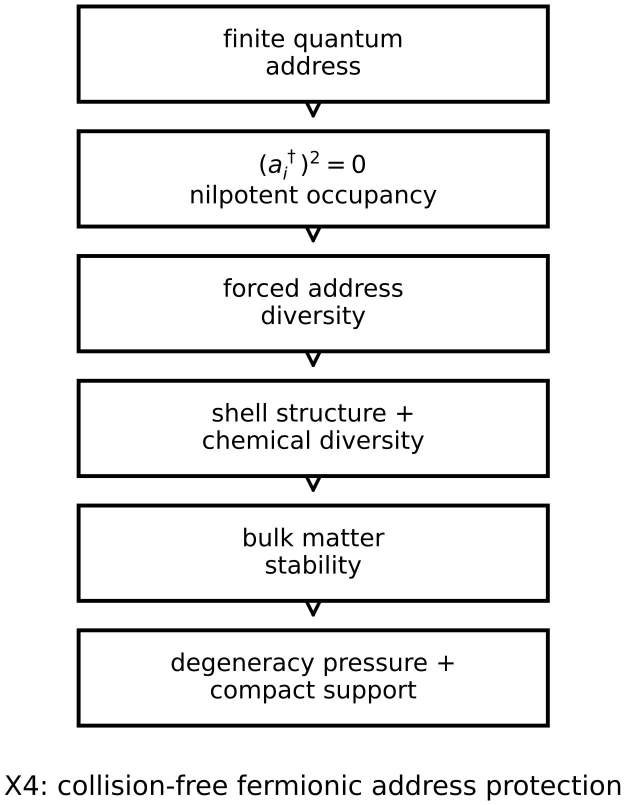

FIG. 6. X4 dependency chain: finite quantum address, nilpotent occupancy, forced address diversity, shell structure, chemical diversity, bulk matter stability, and degeneracy-pressure support.

RELATION TO EXISTING THEORY

X4 does not replace the theories in Table II. It uses them as the standard physics baseline and adds an FDS interpretation of the operational role played by fermionic single-address occupancy.

Table II. Relation of X4 to existing theory.

Theory	What it provides	X4 use
Pauli exclusion	Single occupancy of identical fermions	Physical address protection.
Spin-statistics theorem	Half-integer spin linked to Fermi statistics	Standard hard theorem; X4 supplies operational interpretation.
Fermionic Fock algebra	Anticommutation and nilpotent creation operators	One-occupancy-event-per-address rule.
Dyson-Lenard / Lieb-Thirring	Mathematical stability of matter	Macroscopic consequence of address protection.
Chandrasekhar / TOV	Compact-object limits from degeneracy pressure and gravity	Astrophysical expression of fermionic address pressure.
Bekenstein / holography	Finite information bounds	Global consistency background, not direct proof.
Parastatistics / anyons	Generalized occupancy and low-dimensional effective statistics	Caveat to the minimality bridge.

DESIGN IMPLICATION FOR PHYSICAL AI

This section is not part of the physics proof. It extracts the FDS design rule implied by X4. Boundary-maintaining agents need Pauli-like address protection: two incompatible identity tokens should not silently occupy the same memory address.

Physics	AI analogue
Fermionic address protection	unique object-token identity slot
Pauli exclusion	collision-free write to an identity slot
Address diversity	separated object files / entity tracks
Shell structure	hierarchical memory allocation
Degeneracy pressure	resistance to representation collapse
Bosonic mode	shared signal / broadcast / attention field

Missing Pauli-like rule	Agent failure mode
Address collision	two entities share one logical slot
Identity overwrite	new object silently overwrites old object
Memory aliasing	one key retrieves incompatible entities
Object permanence failure	identity not preserved across time
Decision collapse	actions target merged or confused entities
Catastrophic forgetting	address reuse destroys prior distinctions

If an agent merges “enemy” and “cover” into one logical address, planning can become physically unsafe. X4 therefore suggests that robust agents should separate identity-bearing tokens from shared broadcast fields, latent attention modes, and global communication channels.

CONCLUSION

Pauli exclusion is not merely a strange rule about antisymmetric wavefunctions. In FDS language, it is finite address protection for fermionic matter. The nilpotency condition $(a_i^\dagger)^2 = 0$ enforces a one-occupancy-event-per-address rule, forcing fermions to occupy distinct modes. This produces shell structure, chemical diversity, matter stability, and degeneracy pressure. X4 does not replace the spin-statistics theorem or derive the Pauli principle from FDS alone. It identifies the operation Pauli exclusion performs in a finite distinction system: it protects matter from identity-address collision and converts finite addressability into structural richness. At the level of FDS memory dynamics, this is a local physical analogue of anti-recurrence: an occupied fermionic address cannot be silently overwritten by an identical occupancy event. Because each address stores at most one occupancy event, it forms a natural anti-overwrite barrier. By preventing address-level identity collisions, PEP maintains the independence of historical records in finite systems and provides a local physical analogue of the P4 anti-recurrence property [2].

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