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ORTHOGONAL REVIEW RECORD

Quaternary Coding Theory of the Biological Ledger over GF(4)

Evaluation Codes, Plaquette Checks,
and Conditional Syndrome Decoding

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Declared review status

This is an AI-assisted simulated orthogonal review, not independently appointed human peer review. Separate mathematics and chemistry passes inform the revision. Concordance compares the manuscript, historical review, executable computations and formal companion. Revision responses describe prepared changes rather than unprovided author statements.

> **Scope of Review**
>
> The controlling input is Article 98's supplied `main.tex`. Its historical report and verification and formal-proof dossiers are evidence to audit. Algebraic codes, channel probabilities, quantum stabilizers and a molecular readout mechanism require distinct claims and evidence.

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1 Source record and historical review

The supplied report is preserved unaltered at `provenance/Article98_Prior_Referee_Source.tex`. Its verdict "Accept (All Five Optional-Argument Bracket Protections & Three Coding-Theoretic Enrichments Verified)" and October/Volume 1 Number 5 metadata are historical, not the disposition of this audit. The earlier report examined protected optional-argument brackets, the dual simplex and tensor-product codes, and CSS orthogonality. It accepted the stated coding gain and Stark savings and described molecular syndrome extraction as established. These are audited below rather than inherited as certification. **`main.tex` SHA-256**

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`FormalProof.tex` SHA-256

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2 Mathematical validity review

> **Mathematical disposition**
>
> Substantial revision of interpretation and evidence is warranted, while the core finite classical codes remain valid: the self-dual $[4, 2, 3]_4$ evaluation code, perfect $[5, 3, 3]_4$ Hamming code, $[20, 6, 9]_4$ tensor-product code and dual $[117, 64, 4]_4/[117, 53, 3]_4$ lattice codes.

2.1 M1 Tensor-product construction and minimum distance

Ordinary symbol-by-symbol concatenation is not defined by sending one $\mathbb{F}_4$ symbol into a dimension-two inner code. Equal cardinalities between codewords and a proposed chemical stock do not give a metric-preserving encoder.

Revision response. The revised product is the array space $G_{\mathrm{loc}}^{\mathsf{T}} M G_5$, with $M \in \mathbb{F}_4^{2\times 3}$. Its columns lie in the locus code and its rows in the contact code. Any nonzero column has at least three nonzero rows; each such row has weight at least three. Thus the array has weight at least nine. A tensor of minimum-weight component words attains nine. The six-dimensional message matrix gives 4096

codewords. Chemical realization is separate.

2.2 M2 CSS commutation and logical dimension

The identity $\partial_1\partial_2 = 0$ is not alone a declaration of a useful quantum memory. A ququart CSS construction requires the trace-symplectic Pauli convention and a rank count. The full box has rank sum $53 + 64 = 117$, so it encodes zero logical ququarts.

Revision response. The revision uses $X(a)|x\rangle = |x + a\rangle$ and $Z(b)|x\rangle = (-1)^{\mathrm{Tr}_{\mathbb{F}_4/\mathbb{F}_2}(bx)}|x\rangle$, with all field multiples of independent check rows. Euclidean orthogonality implies commutation. Deleting r independent field-valued constraints from chosen row bases yields r logical ququarts; deleting a redundant displayed row need not change rank. No positive quantum distance or circuit threshold follows from the classical distances three and four.

2.3 M3 Ideal decoding and the fully randomizing limit

For $y = c+e$, the perfect nearest-codeword decoder returns the transmitted c exactly when $\mathrm{wt}(e) \leq 1$. With independent common total symbol-error probability p, its exact failure probability is

$$P_{\mathrm{fail}} = 1 - (1-p)^5 - 5p(1-p)^4 = 10p^2 - 20p^3 + 15p^4 - 4p^5.$$

The nonzero error amplitudes need not have equal conditional probabilities for this event calculation. Perfect syndrome acquisition and correction are required.

Revision response. The revision states these assumptions and separates ideal error correction from fault tolerance of a noisy physical circuit. At $p = 3/4$ for a fully uniform quaternary channel, success is $1/64$ and failure $63/64$. The output carries no information about the input. Rate $3/5$, redundancy and decoder cost are kept visible rather than claiming high-fidelity survival through complete randomization.

2.4 M4 Thermal laws and corrected benchmarks

The source uses a binary logistic total-error law while describing quaternary thermal contacts. For one target and g degenerate adverse levels, the inverse law is $\Delta = k_B T \ln[g(1-p)/p]$. The distinction affects the absolute splitting and percentage reduction.

Revision response. At 300 K, the corrected coded target is $p = 0.0326821122$. For the five-contact comparison under the effective binary law, the uncoded and coded splittings are approximately 160.5043 and 87.5788 meV, a 45.4352% reduction. The literal symmetric four-level law adds $k_B T \ln 3 \simeq 28.4013$ meV to each: 188.9056 and 115.9801 meV, a 38.6042% reduction. At uncoded block failure 0.05 and 0.01, coding gains are approximately 48.9923 and 248.9985. These replace the stale source values. Splitting, barrier, field and total work are not equated.

2.5 M5 Lattice code proofs and decoding scope

The graph's 64-dimensional cycle space is distinct from the vanishing first homology of the plaquette-filled complex. Weighted nonzero cycles over $\mathbb{F}_4$ still have support containing an ordinary graph cycle. The cut-distance proof requires edge connectivity three.

Revision response. The revision establishes $\operatorname{im}\partial_2 = \ker\partial_1$ by the stated complex argument and explicit ranks. A shortest ordinary cycle has four edges and an elementary plaquette attains that weight. The elementary slice argument for edge connectivity, independently checked by unit-capacity max-flow, and a three-edge corner cut establish cut distance three. The cut-code syndrome therefore detects every one- or two-edge substitution and uniquely corrects any single-edge substitution anywhere, not only errors localized to a vertex star.

2.6 M6 Ideal syndrome instrument and physical implementation

Two quaternary syndrome symbols require sixteen outcomes, equivalent to four binary bits. Two binary flux parities cannot identify all fifteen nonzero syndromes. Classical correction also does not by itself correct arbitrary quantum phase errors.

Revision response. The revision explicitly constructs the syndrome-sector measurement instrument and states its code-space preservation property. The existence of that mathematical instrument is not proof of the proposed Berry-phase coupling, a nondemolition apparatus or absence of disturbance for arbitrary quantum data. Molecular implementation remains conditional.

3 Concordance review

> **Concordance disposition**
>
> The original Python and eleven-theorem Lean listing pass fresh execution. The principal defects are overstated coverage and stale manuscript constants, not compilation failures. Passing code cannot certify claims absent from its source.

3.1 C1 Python coverage

The supplied lattice block counts vertices, edges and faces and emits rank and distance values without constructing the boundary matrices, checking their product, computing ranks or proving distances. The product-code block uses parameter arithmetic rather than enumerating the product code. Several advertised field and MacWilliams tests are absent.

Revision response. The replacement suite constructs the matrices and field operations, computes ranks, verifies boundary composition and girth and max-flow witnesses, enumerates the tensor-product code and checks decoder behavior. Checks are explicit rather than dependent on Python assertions disabled by optimized mode. Negative controls test rejection of deliberately incorrect claims. The companion maps each block to its precise coverage.

3.2 C2 Formal proof provenance and scope

The inherited eleven-theorem Lean listing compiles. Its distance declarations prove lower bounds but lack attaining witnesses; self-orthogonality alone is not a proof of equality with the full dual space. Its decoder theorem addresses contact zero, not every position. It has no product-code, lattice, thermal or molecular proof. The declaration named `gf4_comm_ring` proves selected identities rather than a complete field structure.

Revision response. The final formal companion expands explicit finite certificates where feasible and states the boundary of coverage. The planar projection is an additive $\mathbb{F}_2$-linear map from three binary coordinates to two, not a unital field or ring homomorphism from GF(8) to GF(4). Formal theorem meanings are read from their statements rather than inferred from their names.

3.3 C3 Constants and cross-article dependencies

The generated and printed source values disagree. Correct rounded values include coded failure 0.001021 and gain 49.0 at the 95% block benchmark; coded failure 0.0000402 and gain 249.0 at the 99% benchmark; and binary-law splittings 160.50/87.58 meV. Approved Article 97 no longer retains the source's literal Target 7.1 label. Articles 96 and 97 now state thermal and physical assumptions more carefully.

Revision response. The revised abstract, figures, conclusion, hypothesis register, verification macros and OJS abstract are synchronized. Article 98 is described as a coding follow-on without asserting an unchanged target number. Earlier Article 4 and 9 molecular proposals are distinguished from the finite code theorems established here. Unverified inherited theorem-number attributions are not treated as newly checked physical evidence.

4 Chemistry and physical interpretation review

> **Chemistry disposition**
>
> Seven recommendations retain the exact code constructions while making molecular implementation, noise, readout and energetic comparisons explicit. Algebraic cardinalities do not validate the proposed apparatus.

4.1 H1 Mathematical indexing and molecular encoding

Sixteen locus-code words can index a sixteen-element stock, but cardinality alone does not establish four independently prepared and measured quaternary symbols at four chemical loci. Likewise, equality between 64 codewords and 64 absolute binary orientations does not preserve locality or error structure. Five relative binary contacts have only 32 assignments. The product code is a 4×5 array, not a substitution of a single quaternary symbol into a dimension-two inner code.

Revision response. The revision treats these as abstract encodings and requires a separate molecular-realization hypothesis: distinguishable physical states, preparation and readout maps, and a correspondence between physical faults and symbol errors. The tensor-product construction is defined by its row and column constraints. No chemical state discrimination follows from the matching cardinalities.

4.2 H2 Sixteen syndromes and nondemolition measurement

The syndrome space $\mathbb{F}_4^2$ has sixteen outcomes. Two binary flux parities provide only four outcomes. An ideal measurement needs two four-outcome observables or an equivalent four-bit outcome register.

Spatial mode orthogonality and zero net charge transfer alone do not establish a nondemolition measurement or negligible backaction.

Revision response. The revision defines syndrome-sector projectors $P_s = \sum_{Hy=s} |y\rangle\langle y|$, whose sum is the identity. The instrument $\rho \mapsto P_s \rho P_s$ preserves code-space states on outcome zero, but generally removes coherence between different syndrome sectors when the result is discarded. A molecular apparatus implementing this instrument is a separate hypothesis, with measurement fidelity, timing and backaction to be tested.

4.3 H3 Aromatic response and Berry-phase claims

An aromatic perimeter and a C_{2h} label do not specify a cyclic parameter path, gapped eigenbundle or quantized Berry phase π. Magnetically induced aromatic currents are not evidence of independently stable circulating flux states. The original information-theoretic optimality claim lacks an objective that includes noise, timing and work.

Revision response. The revision distinguishes the algebraic syndrome instrument from a proposed ring-current or flux implementation. Berry-phase quantization and topological protection require their own Hamiltonian and symmetry conditions. Universal optimality is not retained; candidate magnetic sensing is presented as an experimental target.

4.4 H4 Total symbol-error probability and thermal calibration

The binomial failure law requires independent contact-error events with common total probability p and an ideal decoder. Equal conditional probabilities among the three nonzero error symbols are additionally needed to call the channel quaternary symmetric. For one correct level and three degenerate wrong levels at splitting Δ, the Gibbs law is

$$p = \frac{3e^{-\beta\Delta}}{1 + 3e^{-\beta\Delta}}, \qquad \Delta = k_B T \ln \frac{3(1-p)}{p}.$$

The binary logistic law is a binary-error surrogate or a calibrated phenomenological total-error law, not generic four-level thermodynamics.

Revision response. The revision distinguishes the degeneracy conventions and reports their numerical consequences. Correlated errors, leakage, erasures, bond loss, and imperfect readout or recovery are outside the independent-symbol theorem. The deterministic single-error guarantee remains valid without a probabilistic model.

4.5 H5 Splitting reduction is not total work or field reduction

The inferred Δ is a state energy or free-energy splitting, not an activation barrier. A Stark relation generally contains offsets, linear dipole terms and quadratic polarizability terms. Percentage reductions in splitting and electric field agree only under a specified proportional calibration. Measurement, recovery, reset, redundancy and dissipation also contribute to total operating cost.

Revision response. The revised comparison fixes temperature and the error-to-splitting law. It distinguishes the five-contact comparison from an equal-payload benchmark: a coded block carries three quaternary information symbols whereas an uncoded five-symbol block carries five. It does not infer total-work, voltage or universal field savings.

4.6 H6 Randomizing channels and classical versus quantum protection

For a fully randomizing quaternary channel, $p = 3/4$ and the output is independent of the input. The perfect decoder succeeds with probability $1/64$, not near unity. Classical bounded-distance correction is not a noisy-apparatus fault-tolerance theorem and does not correct arbitrary quantum phase errors. The complete box CSS check ranks sum to 117, so the unpunctured construction has zero logical ququarts.

Revision response. The revision identifies the channel regime and distinguishes classical code distance from quantum memory parameters. Removing independent check constraints can introduce logical degrees of freedom, but no useful quantum distance or threshold is inferred without analysis. "Maximum entropy" is not used to promise recovery through a fully randomizing channel.

4.7 H7 Empirical closure

A staged implementation test should characterize the substituted stack, four distinguishable contact states, preparation and measurement, calibrated Stark response, total and conditional error rates, correlations, all sixteen syndrome outcomes, backaction and leakage, and recovery of all fifteen single errors. Multi-error miscorrections, equal-payload performance and whole-cycle work should be measured separately.

Revision response. These are prospective tests, not experimental results. NV or SQUID sensing is a proposed component rather than an established molecular syndrome instrument. A demand to discard the finite coding theory solely because the molecular apparatus remains unbuilt is not adopted; the realization assumptions and testable consequences are instead made explicit.

5 Revision decisions and evidence boundaries

> **Prepared revision**
>
> All numbered recommendations are accepted in a scope-preserving form. The finite code constructions and ideal decoder guarantees are retained. No demand for a completed molecular experiment is adopted as a prerequisite for a conditional mathematical paper. Unsupported physical apparatus, quantum-memory, field-saving and maximum-randomization claims are not retained as established results.

The evidence is separated into exact finite algebra and combinatorics, analytic channel probabilities under stated assumptions, numerical thermal calibrations, and proposed physical realization. Neither the review record nor the count of executed checks confers experimental validation or editorial acceptance.

6 Final verification and review closure

The replacement Python suite executes 110,516 explicit checks in each of normal and optimized modes: 110,509 exact and seven numerical, including ten negative controls. It enumerates all 4096 tensor-product codewords, the full 1024-word contact receive space and all 64×16 transmitted-

word/single-error cases. The lattice checks construct the 54×117 incidence matrix and 84 plaquettes, verify ranks 53 and 64 and boundary composition, establish girth and edge-connectivity through explicit graph searches and max-flow, and check all one- and two-edge substitution syndromes. Counts describe executed predicates, not independent theorems.

Lean 4.24 freshly compiles 33 named axiom-free finite certificates. The coverage includes field identities, inverses, distance witnesses, the full contact decoder and all five error positions. It does not formalize the tensor-product distance theorem, full lattice ranks and minimum distances, logarithmic probability calibration, or molecular realization. The complete source and dependency audit in the companion control the formal claim.

The original passing artifacts remain preserved for provenance, while the new dossiers correct the earlier coverage claims. General proofs rely on the manuscript's arguments where they lie beyond the finite formal certificates. Focused post-revision mathematical, concordance and chemistry checks support the scope-preserving repairs. The final refinement supplies an elementary slice proof for edge connectivity, defines the Gibbs splitting per error level before applying degeneracy, and adds explicit multi-error and leakage tests to the prospective experimental plan. These checks close the numbered recommendations for preparation of the revised package, not for experimental validation or a journal acceptance decision.

7 Selected references for physical interpretation

The following sources support distinctions used in the review; none validates the proposed substituted-chrysene apparatus.

1. Braginsky, V. B., Vorontsov, Y. I., and Thorne, K. S. (1980). Quantum nondemolition measurements. *Science* 209, 547–557. https://doi.org/10.1126/science.209.4456.547.

2. Knill, E., and Laflamme, R. (1997). Theory of quantum error-correcting codes. *Physical Review A* 55, 900–911. https://doi.org/10.1103/PhysRevA.55.900.

3. Berry, M. V. (1984). Quantal phase factors accompanying adiabatic changes. *Proceedings of the Royal Society A* 392, 45–57. https://doi.org/10.1098/rspa.1984.0023.

4. Bublitz, G. U., and Boxer, S. G. (1997). Stark spectroscopy: applications in chemistry, biology, and materials science. *Annual Review of Physical Chemistry* 48, 213–242. https://doi.org/10.1146/annurev.physchem.48.1.213.

5. Shannon, C. E. (1948). A mathematical theory of communication. *Bell System Technical Journal* 27, 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.

6. Lovchinsky, I., et al. (2016). Nuclear magnetic resonance detection and spectroscopy of single proteins using quantum logic. *Science* 351, 836–841. https://doi.org/10.1126/science.aad8022. Cited as measurement precedent, not a demonstration of the proposed ring-current decoder.