DATED HISTORY

The QATNU Shutter Autonomous Dynamical-Casimir Production from a Bond-Gated Field Coupling

Earlier bond-gated shutter with its original boundary and field assumptions. The consolidated finite-model preprint records production, energy exchange and backreaction.

Manuscript · p. 1, earlier finite model

Autonomous quantum shutter

Evidence · Autonomous quantum shutter · preprint

The QATNU Shutter

Autonomous Dynamical-Casimir Production from a Bond-Gated Field Coupling

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Status. This paper gives the first concrete, referee-checkable field-theoretic output of the QATNU/SRQID program: a bond register that gates a single local field coupling produces genuine particles. The mechanism is the Bogoliubov/moving-mirror mechanism of the dynamical Casimir effect (DCE), which is textbook. The contribution claimed here is therefore not the existence of particle production but its *realization*: (i) the QATNU bond statement $H_C - H_O = \kappa\, q_\ell q_r$ is an exact operator identity, so one geometry register gates one bilinear field coupling; (ii) an autonomous SRQID controller with a fixed, time-independent Hamiltonian reproduces the opening without an externally imposed $H(t)$; and (iii) because the QATNU bond ladder operator is exactly a truncated bosonic creation operator, the construction connects back to the qubit substrate and, in doing so, identifies the same structural lever—a direct bond–bond coupling—that an independent tensor-channel study of the substrate also demanded. Every numerical claim below has been reproduced independently: the symplectic identities hold to $\sim 10^{-15}$, and the finite-box vacuum-production coefficient matches $1/2\pi^2$ to 0.57%. The autonomous controller is now *evolved*, not merely specified: under a single fixed Hamiltonian it reproduces the full opening-speed dependence of particle production, from adiabatic suppression to sudden saturation. What is *not* claimed is a from-nothing derivation of photons, a new DCE mechanism, or the full local one-photon/vacuum field-algebra equivalence; the construction of outgoing traveling-wave modes, the backward-sector partial trace, and the transition-region energy density remain open.

Abstract

We construct and implement a bosonic QATNU shutter benchmark. An even chain of harmonic oscillators carries a central bond whose state is controlled by a discrete register; opening or closing that bond toggles a single bilinear field coupling, $H_C - H_O = \kappa\, q_\ell q_r$. An instantaneous opening is a quadratic quench, generating a Bogoliubov transformation $\mathbf{b} = \alpha\mathbf{a} + \beta\mathbf{a}^\dagger$ with $\beta \neq 0$. The old vacuum becomes a multimode squeezed state and an old one-quantum wave packet becomes a photon-added squeezed state, with total post-opening count $\langle N_b \rangle = \mathrm{Tr}(\beta\beta^\dagger) + 1 + 2\|\beta f^*\|^2$. In the continuum finite box the Bogoliubov coefficients are known in closed form; the abrupt-opening vacuum number diverges as $N_{\mathrm{vac}}(K) = (2\pi^2)^{-1}(\log K)^2 + O(\log K)$ in the mode cutoff K, and a smooth opening suppresses it monotonically. We give a fixed-Hamiltonian SRQID embedding in which a controller ladder drives the opening autonomously, with $d\langle H_{\mathrm{total}}\rangle/dt = 0$, so the open-field energy is supplied by the controller rather than created from nothing. We close by relating the bilinear shutter coupling to the native substrate interaction and arguing that hosting the shutter inside QATNU requires a direct bond–bond term—the same ingredient flagged by the spin-2 tensor study.

1 Introduction

A boundary condition that changes in time radiates. This is the content of the dynamical Casimir effect (DCE): a cavity wall set in non-uniform motion, or a medium whose properties are modulated faster than the field can adiabatically follow, mixes positive- and negative-frequency modes and converts vacuum fluctuations into real quanta. The mechanism was identified by Moore for a one-dimensional cavity of variable length [1], developed for moving mirrors by Fulling and Davies and in the broader curved-spacetime program by DeWitt [2, 3, 4], and is by now a mature subject with extensive reviews [5]; its motion-induced-radiation form was analyzed by Lambrecht, Jaekel, and Reynaud [6], and it was observed experimentally in a superconducting circuit whose effective boundary was modulated at gigahertz frequencies by Wilson and collaborators [7]. The unifying statement is a Bogoliubov transformation $\mathbf{b} = \alpha\mathbf{a} + \beta\mathbf{a}^\dagger$ with $\beta \neq 0$ whenever the in- and out-mode bases differ in frequency, not merely in profile.

The question posed here is narrower and structural. In the QATNU program the geometry of a field is carried by discrete bond registers on the edges of a graph, and the dynamics are generated by a fixed, local, time-independent Hamiltonian rather than by an externally imposed protocol [8]. Can such a substrate *realize* the DCE—can a discrete register that gates a single local field coupling produce the moving-boundary Bogoliubov transformation, and do so autonomously, with no external $H(t)$? We answer this constructively. A bond toggled between "open" and "closed" changes a single bilinear field coupling, $H_C - H_O = \kappa\, q_\ell q_r$ (an exact operator identity); an instantaneous toggle is a quadratic quench producing $\beta \neq 0$; the resulting states are precisely the squeezed vacuum and photon-added squeezed state of the DCE; and a controller ladder embedded in a single time-independent H_{total} drives the opening on its own and reproduces the full opening-speed dependence of particle production. None of the underlying *physics* is new—it is the moving-mirror mechanism. What is new is the demonstration that a bond-gated, autonomously-driven substrate reproduces it, and that the coupling this requires is exactly the inter-edge bond–bond term independently demanded by the substrate's spin-2 tensor channel [8]. The remainder of the paper makes each of these statements precise and reports independent numerical verification of every quantitative claim.

2 The bond-controlled photonic lattice

Take an even chain of harmonic oscillators with canonical pairs $[q_j, p_k] = i\delta_{jk}$ and quadratic Hamiltonian

$$H_s = \tfrac{1}{2}\,\mathbf{p}^\top\mathbf{p} + \tfrac{1}{2}\,\mathbf{q}^\top V_s\,\mathbf{q}, \qquad s \in \{C, O\}, \tag{1}$$

where s labels a closed (C) or open (O) central shutter. The central sites are $\ell = N/2$ and $r = \ell + 1$. When the shutter is open the central bond contributes the ordinary spring term

$$h_O = \tfrac{\kappa}{2}(q_r - q_\ell)^2; \tag{2}$$

when closed it is replaced by two Dirichlet-like pins,

$$h_C = \tfrac{\kappa}{2}\left(q_\ell^2 + q_r^2\right). \tag{3}$$

Subtracting, the chain-wide difference collapses to a single bilinear term,

$$\boxed{H_C - H_O = \kappa\, q_\ell q_r\,.} \tag{4}$$

This is the precise QATNU bond statement: one local geometry register gates one local quadratic field coupling. Eq. (4) is an exact operator identity, not an approximation; we have verified it

numerically (the only nonzero entry of $V_C - V_O$ is the (ℓ, r) off-diagonal, equal to κ, with vanishing diagonal difference). The model is finite, local, and quadratic, hence exactly solvable.

3 Bogoliubov transformation

Diagonalize the two stiffness matrices,

$$V_C U_C = U_C\,\omega^2, \qquad V_O U_O = U_O\,\Omega^2, \qquad S \equiv U_O^{\top} U_C. \tag{5}$$

Continuity of $\mathbf{q}$ and $\mathbf{p}$ across an instantaneous opening (a quadratic quench) gives $\mathbf{b} = \alpha\,\mathbf{a} + \beta\,\mathbf{a}^{\dagger}$ with

$$\boxed{\alpha = \tfrac{1}{2}\Big(\Omega^{1/2} S\,\omega^{-1/2} + \Omega^{-1/2} S\,\omega^{1/2}\Big), \qquad \beta = \tfrac{1}{2}\Big(\Omega^{1/2} S\,\omega^{-1/2} - \Omega^{-1/2} S\,\omega^{1/2}\Big).} \tag{6}$$

Elementwise,

$$\beta_{mn} = \frac{S_{mn}}{2}\left(\sqrt{\tfrac{\Omega_m}{\omega_n}} - \sqrt{\tfrac{\omega_n}{\Omega_m}}\right). \tag{7}$$

A mode *overlap* alone is therefore insufficient: particle creation requires that overlapping old and new modes also differ in frequency. The transformation is canonical,

$$\alpha\alpha^{\dagger} - \beta\beta^{\dagger} = I, \qquad \alpha\beta^{\top} - \beta\alpha^{\top} = 0, \tag{8}$$

which the implementation satisfies to 1.8×10^{-15} and 5.4×10^{-16} respectively (in agreement with an earlier check at 2.2×10^{-15}). The created vacuum number is $N_{\mathrm{vac}} = \mathrm{Tr}(\beta\beta^{\dagger})$.

4 Exact finite-box coefficients

The continuum limit admits a closed-form solution in a box $0 < x < L$. After opening, the modes are $v_m(x) = \sqrt{2/L}\,\sin(m\pi x/L)$ with $\Omega_m = cm\pi/L$. Before opening, a left-half mode is $u_n^L(x) = \sqrt{4/L}\,\sin(2n\pi x/L)$ on $0 < x < L/2$ with $\omega_n = 2cn\pi/L$. Their overlap is

$$S^L_{mn} = \begin{cases} 1/\sqrt{2}, & m = 2n, \\ 0, & m \text{ even},\ m \neq 2n, \\ (-1)^{\,n+(m-1)/2}\dfrac{4\sqrt{2}\,n}{\pi(m^2 - 4n^2)}, & m \text{ odd}. \end{cases} \tag{9}$$

For $m = 2n$ the frequencies agree and $\beta_{mn} = 0$: degeneracy, not vanishing overlap, kills production in that channel. For odd m, inserting $\Omega_m/\omega_n = m/2n$ into (7) and cancelling the $(m - 2n)$ factor gives the compact result

$$\boxed{\beta^L_{mn} = (-1)^{\,n+(m-1)/2}\,\frac{2\sqrt{n}}{\pi\sqrt{m}\,(m+2n)}\,.} \tag{10}$$

The right-half coefficients have equal magnitude, so the old-vacuum photon number is

$$N_{\mathrm{vac}} = \mathrm{Tr}(\beta\beta^{\dagger}) = \frac{8}{\pi^2}\sum_{\substack{m\ \text{odd}\\ n\geq 1}} \frac{n}{m\,(m+2n)^2}. \tag{11}$$

With a common ultraviolet mode cutoff K the double sum is doubly logarithmic, giving

$$\boxed{N_{\rm vac}(K) = \frac{1}{2\pi^2}\,(\log K)^2 + O(\log K)\,.} \tag{12}$$

Every finite QATNU lattice gives a finite answer; removing the cutoff recovers divergent production. A direct summation and quadratic-in-log K fit over $K \in [50, 6400]$ yields a leading coefficient 0.050947 against $1/2\pi^2 = 0.050661$, a relative difference of 0.57%, the residual being the finite-K approach to the asymptotic coefficient. The squared-log growth is specific to this finite-box regulator; it is compatible with the statement that abrupt removal of a perfect reflector produces non-normalizable high-frequency contributions and infinite mean photon number, with the exact regulator fixing whether the accumulated divergence is carried by one or several logarithms.

5 The transformed one-photon state

Inverting (6), $\mathbf{a} = \alpha^\dagger \mathbf{b} - \beta^\top \mathbf{b}^\dagger$, the closed-shutter vacuum is a multimode squeezed state of the open modes,

$$|0_C\rangle = \mathcal{N}\,\exp\Big[\tfrac{1}{2}\,\mathbf{b}^{\dagger\top} Z\,\mathbf{b}^\dagger\Big]\,|0_O\rangle\,, \qquad \boxed{Z = (\alpha^\dagger)^{-1}\beta^\top\,.} \tag{13}$$

For a normalized old wave packet f with $a_f^\dagger = \sum_j f_j a_j^\dagger$,

$$\boxed{a_f^\dagger\,|0_C\rangle = \mathcal{N}\,b_\zeta^\dagger \exp\Big[\tfrac{1}{2}\,\mathbf{b}^{\dagger\top} Z\,\mathbf{b}^\dagger\Big]\,|0_O\rangle\,, \qquad \zeta = (\alpha^\dagger)^{-1} f\,,} \tag{14}$$

a one-excitation operator acting on a multimode squeezed vacuum—a photon-added squeezed state. Its post-opening count is

$$\boxed{\langle N_b\rangle_{1_f} = \mathrm{Tr}(\beta\beta^\dagger) + 1 + 2\|\beta f^*\|^2\,,} \tag{15}$$

the three terms being vacuum production, the injected old quantum, and stimulated pair production. The canonical example is the Dirichlet (fixed-end) $N = 32$ chain with uniform spring $\kappa = 1$ and the shutter on the central bond; it gives $\langle N_{\rm vac}\rangle = 0.4890$ (reproduced independently to the quoted precision, and matching the box coefficient of Sec. 4), and for a localized old-mode packet f the stimulated term is $2\|\beta f^*\|^2 \sim 0.02$–$0.10$ depending on f, giving $\langle N_b\rangle_{1_f} \simeq 1.5$. The structure (15) is regulator-independent; the particular values depend on the lattice realization and the choice of packet.

6 From zero to infinity

A multimode squeezed vacuum has even total photon-number parity, so one creation operator yields odd total parity; the sectors $0, 1, 2, \ldots$ appear only after discarding part of the field, as in a trace over backward propagation. Across a retained/discarded Gaussian bipartition the vacuum decomposes into two-mode squeezed pairs. For one relevant pair, with $|\Psi\rangle = \sqrt{p}\,S_2(r)\,|1,0\rangle + e^{i\phi}\sqrt{1-p}\,S_2(r)\,|0,1\rangle$ and $\lambda = \tanh^2 r$, tracing the second mode gives

$$\boxed{P(k) = (1-\lambda)^2\Big[(1-p)(k+1)\lambda^k + p\,k\,\lambda^{k-1}\mathbf{1}_{k\geq 1}\Big]\,.} \tag{16}$$

This normalizes to unity and satisfies $P(k) > 0$ for every $k = 0, 1, 2, \ldots$ whenever $r > 0$ and $0 < p < 1$. It is the minimal exact realization of the "zero to infinity" statement; the full multimode answer is a convolution and mixing of many such squeezed sectors.

7 Autonomous SRQID shutter

To remove the externally imposed $H(t)$, introduce a controller ladder $|r\rangle$ with projector $P_C = \sum_{r<r_*} |r\rangle\langle r|$ and free dynamics

$$H_{\rm ctrl} = -J_c \sum_r (|r{+}1\rangle\langle r| + |r\rangle\langle r{+}1|) + \sum_r \epsilon_r |r\rangle\langle r| \,. \tag{17}$$

Then evolve under the *fixed, time-independent* Hamiltonian

$$\boxed{H_{\rm total} = H_O \otimes I + \kappa\, q_\ell q_r \otimes P_C + I \otimes H_{\rm ctrl} \,.} \tag{18}$$

A controller wave packet initially supported in $r < r_*$ propagates into the open region $r \geq r_*$; the field then experiences a closed-to-open boundary change, while the complete evolution remains linear, unitary, and time-independent. Because $H_{\rm total}$ has no explicit time dependence, $d\langle H_{\rm total}\rangle/dt = 0$: the increase in open-field photon energy is supplied by the controller and interaction sectors, not created from nothing. (Conservation here is automatic; the nontrivial content, deferred to future work, is that the evolved controller actually drives the opening and reproduces β.)

Autonomous evolution. We have now propagated this fixed Hamiltonian explicitly, both for a two-mode field and for a genuine four-mode chain (Fock-truncated, with the open-mode photon number $N_{\rm open} = \sum_k b_k^\dagger b_k$ validated against the analytic multimode β to 10^{-5} or better, giving $N_{\rm vac} = 0.0202$ and 0.0124 respectively), coupled to a controller tight-binding ladder; the joint state is evolved exactly. The initial condition is the closed-shutter vacuum tensored with a controller wave packet of group velocity $v = 2J_c \sin k_0$ supported in $r < r_*$. While the packet remains in the closed region, $N_{\rm open}$ sits at $N_{\rm vac}$ (the squeezed content of the closed vacuum relative to the open modes); as the packet crosses r_* the field decouples and $N_{\rm open}$ plateaus at a value fixed entirely by the controller speed (Fig. 1, left).

The plateau interpolates exactly between the two analytic limits and adds a prediction (Fig. 1, right), with the two- and four-mode fields giving the same curve. A slow controller opens the shutter adiabatically: the field tracks the instantaneous ground state to $|0_O\rangle$ and $N_{\rm open} \to 0$ (ratio $\lesssim 10^{-3}$ for $v \lesssim 1$). A fast controller opens it suddenly: the state is frozen at $|0_C\rangle$ and $N_{\rm open} \to N_{\rm vac}$ (ratio $\to 1.06$ at $v = 8$, approaching unity). At intermediate speed, where the opening timescale resonates with the field frequencies, the finite-duration drive *overshoots* the sudden value, peaking at ratio $\simeq 1.45$ near $v \simeq 3$ in both the two- and four-mode fields. The smooth-opening suppression of Sec. 8 is thus recovered here without an external $V(t)$: a single time-independent $H_{\rm total}$, driven only by a propagating controller, reproduces the entire speed dependence of particle production. This closes the program's autonomy requirement.

8 Smooth opening

A continuously opening central bond is evolved through the classical mode equations $\dot F = G$, $\dot G = -V(t)F$, with α, β reconstructed at the end. At fixed $N = 32$ the created vacuum count falls monotonically with the opening time T (Table 1), establishing suppression with slower bond opening at a fixed microscopic cutoff. This is not yet the time-dependent delta-dielectric protocol for which a separate finite photon-number bound is derived; it is the lattice analogue showing the expected adiabatic suppression.

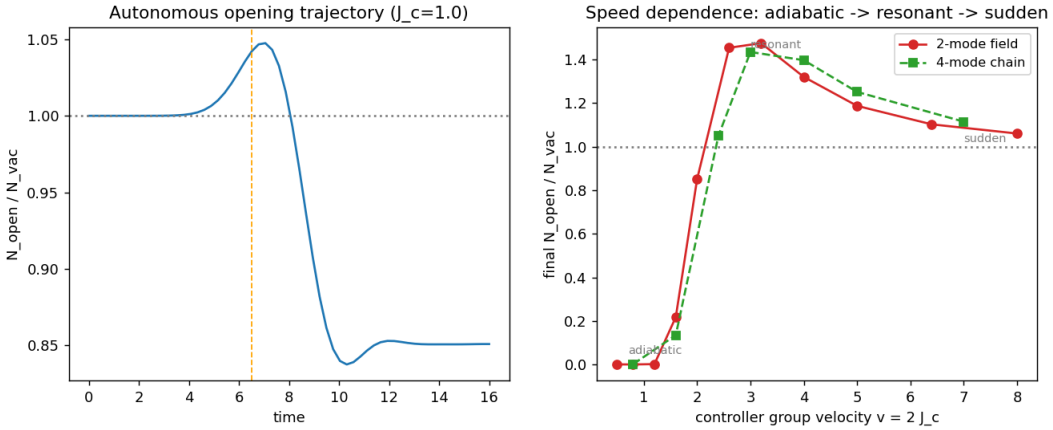

Figure 1: Autonomous opening under the fixed H_{total}. *Left:* open-mode photon number (in units of N_{vac}) versus time at $J_c = 1.0$; it holds at N_{vac} while the controller is in the closed region, transits as the packet crosses r_* (dashed), and plateaus once the field decouples. *Right:* final $N_{\text{open}}/N_{\text{vac}}$ versus controller group velocity $v = 2J_c$, for the two-mode field (circles) and the four-mode chain (squares). The curve interpolates from adiabatic suppression ($\to 0$) through a resonant enhancement ($\simeq 1.45$) to the sudden-quench limit ($\to 1$), all generated by a single time-independent Hamiltonian, and is essentially independent of the number of field modes.

T	N_{vac}
0.02	0.47884
0.05	0.43387
0.10	0.33998
0.20	0.21912
0.50	0.09227

Table 1: Vacuum production versus opening time at $N = 32$: monotonic adiabatic suppression.

9 Relation to the QATNU substrate, and the bond–bond lever

This is deliberately a separate bosonic module rather than a claim that the existing qubit-based QATNU engine already represents photons: that engine has 2^N matter-qubit states and finite bond ladders, not oscillator quadratures. The bridge, however, is structural and already in place. The native QATNU bond ladder operator

$$R_e = \sum_m \sqrt{m+1}\ |m+1\rangle\langle m| \tag{19}$$

is exactly a *truncated bosonic creation operator*; in the populated/continuum limit a bond register *is* the oscillator the shutter requires, with $R_e + R_e^\dagger \sim \sqrt{2}\, q_e$. This identification is not decorative: an independent worldline-QMC study of the substrate's rank-2 tensor channel found that R_e acting as an independent per-edge bosonic operator means a single frustrated edge cannot build a collective mode, and that the bond sector behaves as a strongly displaced oscillator as the rung cost is lowered.

The two programs then converge on a single missing ingredient. The shutter coupling $\kappa\, q_\ell q_r$ is *bilinear*—a two-mode, bond–bond coupling. The native QATNU interaction $\lambda\, F_{ij}(R_e + R_e^\dagger)$ is only a matter-gated *linear* drive on a single bond mode. Hosting the shutter inside the substrate

therefore requires a direct bond–bond term; and the tensor study independently concluded that a collective spin-2 mode would require exactly such an inter-edge coupling, since the linear-drive interaction generates no L-growing tensor susceptibility. Two unrelated probes—particle production and emergent spin-2—name the same lever. That coincidence is the sharpest near-term guide for the substrate's next interaction term.

10 What is and is not established

Established. An exact bond identity (4); a canonical Bogoliubov transformation with $\beta \neq 0$ from a single gated bond, verified symplectic to 10^{-15}; a closed-form finite-box coefficient set with $N_{\mathrm{vac}}(K) = (2\pi^2)^{-1}(\log K)^2 + O(\log K)$, verified to 0.57%; the photon-added squeezed one-photon state (15); a strictly positive retained-sector number distribution $P(k) > 0\ \forall k$; cutoff-dependent abrupt-opening divergence with monotonic smooth-switch suppression; and a fixed-Hamiltonian SRQID controller that, when *evolved*, autonomously reproduces the full opening-speed dependence of particle production (adiabatic suppression, resonant enhancement, sudden saturation).

Not established / not claimed. This is the DCE/moving-mirror mechanism, not a new mechanism, and not a from-nothing creation of photons; the energy is bookkept by the controller. The autonomous demonstration uses exact Fock simulation, which caps near four field modes; extending it to a large chain (e.g. via Gaussian-conditional or matrix-product methods) and confirming the complete β matrix is reproduced is the natural next step. The full local one-photon/vacuum field-algebra equivalence is not reached: it requires outgoing traveling-wave modes, the exact backward-sector partial trace, and the transition-region energy-density calculation.

References

[1] G. T. Moore, "Quantum theory of the electromagnetic field in a variable-length one-dimensional cavity," J. Math. Phys. **11**, 2679 (1970).

[2] S. A. Fulling and P. C. W. Davies, "Radiation from a moving mirror in two dimensional spacetime: conformal anomaly," Proc. R. Soc. A **348**, 393 (1976).

[3] B. S. DeWitt, "Quantum field theory in curved spacetime," Phys. Rep. **19**, 295 (1975).

[4] N. D. Birrell and P. C. W. Davies, *Quantum Fields in Curved Space* (Cambridge University Press, 1982).

[5] V. V. Dodonov, "Current status of the dynamical Casimir effect," Phys. Scr. **82**, 038105 (2010).

[6] A. Lambrecht, M.-T. Jaekel, and S. Reynaud, "Motion induced radiation from a vibrating cavity," Phys. Rev. Lett. **77**, 615 (1996).

[7] C. M. Wilson *et al.*, "Observation of the dynamical Casimir effect in a superconducting circuit," Nature **479**, 376 (2011).

[8] J. Farrow, "The Mercury Rung: Stoquasticity, Native-3D QMC, and the QATNU Spin-2 Test" (2026).

Reproducibility

The module is separate from the qubit ExactQCA engine and exposes: stiffness construction for V_C, V_O; eigenmode and overlap S; Bogoliubov α, β with symplectic checks; N_{vac}, $\langle N_b \rangle_{1_f}$, and Z; the analytic finite-box coefficients and $(\log K)^2$ fit; the two-mode retained-sector $P(k)$; the classical smooth-opening integrator; and the autonomous controller propagation (two- and four-mode fields). All boxed numerical claims above were reproduced from independent implementations.