Fundamental Quantum Theories and Physical Bounds in Adversarial Cryptanalysis: A Unified Framework

VICTORIA MELLOR
School of Computing, Mathematics and Physics, Faculty of Technology,
University of Portsmouth, Portsmouth,
UK

Abstract: - Quantum key distribution (QKD) and postquantum cryptographic systems rely on physical properties for security guarantees. However, the weaponization of quantum phenomena by adversaries necessitates a comprehensive theoretical framework grounding attack surfaces in fundamental physics. We present a unified framework integrating Bose-Einstein statistics, Schrödinger wave mechanics, Heisenberg uncertainty relations, Noether's symmetry theorem, Jackson's semiconductor physics, and Dirac's quantum field formalism to characterize, predict, and detect physical-layer attacks on quantum cryptographic systems. This framework reveals that all attacks manifest as violations of fundamental symmetries, enabling comprehensive detection through conserved quantity monitoring. I demonstrate how material constraints defined by semiconductor physics bound the parameter space of exploits, while Noether's theorem provides the mathematical foundation for complete attack attribution. The synthesis yields both theoretical attack bounds and practical detection methodologies, validated against documented quantum cryptanalyses including detector blinding, photon-number splitting, decoherence engineering, and spectral separation attacks.

Key-words: - Quantum cryptography, adversarial physics, Noether's theorem, physical sidechannels, detector attacks, symmetry violation, quantum key distribution

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1 Introduction

Quantum cryptography promises information-theoretic security grounded in the laws of physics [1, 2]. Yet as quantum key distribution systems transition from laboratory demonstrations to deployed infrastructure, the assumption that physical processes are inherently trustworthy has proven dangerously naive [3, 4, 5]. Practical attacks exploiting detector imperfections, channel manipulations, and entropy source biases have systematically demonstrated that the quantum-classical boundary represents not a security guaranty but an attack surface [6].

Previous work in quantum adversarial physics [15, 16] has catalogued physical-layer attacks and developed statistical detection frameworks such as Resonant Entropy Dislocation Attack

(REDA) analysis. However, these approaches have lacked a unified theoretical foundation connecting attack mechanisms to fundamental physical principles. Without such grounding, security analysis remains reactive—responding to discovered attacks rather than systematically predicting the complete attack surface.

This paper addresses this gap by synthesizing six foundational theoretical frameworks: (1) Bose-Einstein statistics governing photon behaviour, (2) Schrödinger wave mechanics describing quantum state evolution, (3) Heisenberg uncertainty relations constraining measurement, (4) Noether's theorem connecting symmetries to conservation laws, (5) Jackson's semiconductor physics defining material implementation bounds, and (6) Dirac's formalism providing rigorous mathematical language and relativistic constraints.

The central thesis is the following: **every physical-layer attack modelled as a Hamiltonian perturbation that biases quantum measurement statistics must break at least one continuous symmetry of the idealised protocol, and the associated conserved charge becomes an observable for detection**. Attacks that operate purely on classical post-processing, or that exploit discrete-symmetry violations, fall outside this first-theorem framework and must be addressed by complementary layers (see Section 4.4). Within its scope, however, this mathematical completeness, derived from Noether's first theorem [17], transforms physical-layer quantum security from an assumption-based discipline to a physics-grounded science.

2 Theoretical Foundations

2.1 Bose-Einstein Statistics and Photon Manipulation

Photons, as bosons with spin-1, obey Bose-Einstein statistics. The average occupation number for a quantum state with energy ε at temperature T is:

$$\langle n \rangle = \frac{1}{e^{\varepsilon/k_B T} - 1} \tag{1}$$

Unlike fermions, multiple identical photons can occupy the same quantum state without restriction. This fundamental property enables several attack vectors:

Photon-Number Splitting (PNS): Bosonic statistics permit multi-photon Fock states to be spatially partitioned. For example, a symmetric 50:50 beam splitter acting on $|2,0\rangle$ yields:

$$|2,0\rangle \rightarrow \frac{1}{2}|2,0\rangle + \frac{1}{\sqrt{2}}|1,1\rangle + \frac{1}{2}|0,2\rangle \tag{2}$$

illustrating that multi-photon pulses can, in principle, be split without disturbance to individual photon states. In the canonical PNS attack on weak coherent source QKD, the pulse population is Poissonian with $P(n) = e^{-\mu}\mu^n/n!$, giving a non-negligible multi-photon probability for typical mean photon number $\mu \sim 0.1$. An adversary who can perform a quantum non-demolition measurement of photon number may block all single-photon pulses, split one photon from each multi-photon pulse, and forward the remainder to the receiver—extracting full bit information while introducing no quantum bit error rate (QBER) increase [19].

Thermal State Injection: By controlling temperature T, adversaries manipulate the photon occupation statistics, biasing the entropy source toward predictable thermal distributions.

2.2 Schrödinger Evolution and Coherence Control

Quantum states evolve according to the Schrödinger equation:

$$i\hbar\frac{\partial |\psi\rangle}{\partial t} = \hat{H} |\psi\rangle \tag{3}$$

In open quantum systems, environmental coupling introduces decoherence, described by the master equation. The effective coherence time under adversarial environmental manipulation is:

$$T_2' = T_2 \cdot e^{-\gamma_{\text{adv}}\varepsilon_{\text{env}}t} \tag{4}$$

where γ_{adv} is the adversary's coupling strength, and ε_{env} is the environmental manipulation intensity [16].

This accelerated decoherence reduces the entropy of quantum measurements:

$$H_{\text{measured}} = H_{\text{ideal}} - \alpha \log_2\left(\frac{T_2}{T_2'}\right) \tag{5}$$

where α is a dimensionless coupling coefficient relating fractional coherence loss to bit-level entropy degradation, to be calibrated empirically for a given receiver implementation.

Pulse Morphing: Adversaries apply unitary transformations:

$$\psi'(t) = M_\theta(\psi(t)) = \psi(t) \cdot e^{i\phi(t,\theta)} \cdot A(\omega,\theta) \tag{6}$$

introducing statistical bias $\Pr[b = 1|\psi'] = \frac{1}{2} + \delta(\theta)$ in measurement outcomes.

2.3 Heisenberg Uncertainty and Measurement Exploitation

The Heisenberg uncertainty principle constrains conjugate observables:

$$\Delta x \cdot \Delta p \geq \frac{\hbar}{2}, \quad \Delta E \cdot \Delta t \geq \frac{\hbar}{2} \tag{7}$$

More generally, for non-commuting operators $\hat{A}$ and $\hat{B}$:

$$\Delta A \cdot \Delta B \geq \frac{|\langle[\hat{A},\hat{B}]\rangle|}{2} \tag{8}$$

Detector Blinding: By saturating single-photon avalanche diodes (SPADs) with bright illumination, adversaries force detectors from the quantum (Geiger) regime into the classical (linear) regime, where uncertainty protection no longer applies [3, 7]. The detector becomes controllable with clicks determined by classical light intensity instead of quantum measurement statistics.

Time-Energy Trade-offs: Short pulses have large energy uncertainty ($\Delta E \cdot \Delta t \sim \hbar$), which adversaries exploit to inject photons at precise times while evading energy-based filtering.

2.4 Noether's Theorem: The Unifying Principle

Emmy Noether's first theorem [17] establishes:

Every differentiable symmetry of the action of a physical system corresponds to a conservation law.

Mathematically, for a system with Lagrangian $\mathcal{L}$ and action $S = \int \mathcal{L}\, dt$, if the action is invariant under a continuous transformation with parameter ε:

$$\delta S = 0 \Rightarrow \frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{q}} \cdot \delta q\right) = 0 \tag{9}$$

In quantum mechanics, this translates (via Ehrenfest's theorem) to:

$$[\hat{H},\hat{G}] = 0 \Rightarrow \frac{d\langle\hat{G}\rangle}{dt} = 0 \tag{10}$$

where $\hat{G}$ is the generator of the symmetry transformation. Strictly, Ehrenfest's theorem gives

$d\langle\hat{G}\rangle/dt = (i/\hbar)\langle[\hat{H},\hat{G}]\rangle + \langle\partial\hat{G}/\partial t\rangle$; the simplified form above assumes $\hat{G}$ has no explicit time dependence, which holds for the four symmetry generators considered in this work.

Fundamental Symmetries in QKD:

- Time translation → Energy conservation: $\langle\hat{H}\rangle = \text{const}$
- Space translation → Momentum conservation: $\langle\hat{p}\rangle = \text{const}$
- Rotation → Angular momentum: $\langle\hat{J}\rangle = \text{const}$
- U(1) gauge → Photon number: $\langle\hat{N}\rangle = \text{const}$

Critical insight: Any Hamiltonian-level adversarial manipulation that biases quantum measurement statistics must break at least one of these continuous symmetries. Therefore, monitoring the corresponding conserved quantities provides broad detection coverage for physical-layer attacks that act through the unperturbed protocol's Hamiltonian.

2.5 Semiconductor Device Physics: Material Bounds

The physical limits within which quantum cryptographic hardware operates are set by semiconductor device physics, a field whose foundations were advanced by Shirley Ann Jackson's career in theoretical condensed-matter physics at Bell Laboratories following her doctoral work in theoretical elementary-particle physics [18]. Single-photon detectors based on avalanche photodiodes have fundamental constraints:

Wavelength-dependent efficiency:

$$\eta(\lambda) = \eta_0[1 - R(\lambda)][1 - e^{-\alpha(\lambda)d}] \tag{11}$$

where $R(\lambda)$ is wavelength-dependent reflectivity, $\alpha(\lambda)$ is the absorption coefficient, and d is the absorption region thickness. For silicon at 850 nm vs 1550 nm, α differs by $\sim 100\times$, creating efficiency mismatches exploitable in spectral separation attacks.

Detector saturation: Carrier density saturation occurs at $n_{\text{sat}} \sim 10^{18}$ cm^{-3}, corresponding to saturation power:

$$P_{\text{sat}} = \frac{n_{\text{sat}} \cdot V_{\text{junction}} \cdot E_{\text{photon}}}{\eta \cdot \tau} \tag{12}$$

Typically $P_{\text{sat}} \sim$ 10–100 μW, defining the threshold for detector blinding attacks.

Temporal response: Carrier transit time (∼10 ps) and avalanche buildup time (∼50 ps) set fundamental limits on timing attack precision. Dead time (∼10-100 ns) creates windows for dead-time manipulation attacks.

2.6 Dirac's Formalism: Mathematical Rigor and Field Theory

Paul Dirac's contributions provide the mathematical language for rigorous attack analysis:

Creation/Annihilation Operators:

$$\hat{a}^\dagger |n\rangle = \sqrt{n+1}\,|n+1\rangle\,, \quad \hat{a}\,|n\rangle = \sqrt{n}\,|n-1\rangle \tag{13}$$

With the canonical commutation relation $[\hat{a},\hat{a}^\dagger] = 1$. This formalism is essential for analysing photon-number attacks.

Time Evolution Operator:

$$\hat{U}(t) = e^{-i\hat{H}t/\hbar} \tag{14}$$

Adversarial perturbations introduce $\hat{H}_{\text{attack}}$, yielding modified evolution:

$$|\psi(t)\rangle = e^{-i(\hat{H}_0+\hat{H}_{\text{attack}})t/\hbar}\,|\psi(0)\rangle \tag{15}$$

Relativistic constraints: The Dirac equation incorporates special relativity, imposing causality constraints on timing attack synchronization over long distances.

3 Unified Attack Taxonomy

Table 1 presents a complete attack taxonomy organized by violated symmetries, demonstrating mathematical completeness: every documented attack violates at least one fundamental symmetry.

4 Noether-Based Detection Framework

4.1 Monitoring Protocol

For comprehensive attack detection, monitor all Noether charges continuously:

Algorithm 1 Symmetry Monitoring

for each symmetry $s \in \{\text{time}, \text{space}, \text{rotation}, \text{gauge}\}$ **do**
  Calculate conserved quantity: $Q_s(t) = \text{Tr}[\hat{\rho}(t)\hat{G}_s]$
  Compute change rate: $\frac{dQ_s}{dt} = \frac{Q_s(t+\Delta t) - Q_s(t)}{\Delta t}$
  Account for natural loss: Γ_{natural} = calibrated system loss
  if $\left|\frac{dQ_s}{dt}\right| > \Gamma_{\text{natural}} + k\sigma_{\text{measurement}}$ **then**
    ATTACK_DETECTED(s)
  end if
end for

where k is the confidence level (typically $k = 3$ for 3σ detections).

4.2 Attack Attribution

Different attacks produce characteristic patterns of symmetry violation:

- Decoherence shaping: $\frac{dE}{dt} \neq 0$ (time symmetry)
- Detector blinding: $\frac{d\langle\hat{N}\rangle}{dt} \gg \Gamma_{\text{loss}}$ (photon number)
- Pulse morphing: Phase coherence $\Phi = |\langle\psi_A|\psi_B\rangle| < 0.9$ (U(1) gauge)
- Spatial attacks: Beam profile asymmetry (momentum conservation)

4.3 Integration with REDA

The Resonant Entropy Dislocation Attack (REDA) framework [15] detects statistical bias through spectral analysis. Combining Noether monitoring (physical-layer) with REDA (statistical-layer) provides comprehensive coverage:

$$\text{Detection} = \text{Noether violations} \cup \text{REDA anomalies} \tag{16}$$

Enhanced Voting Algorithm: To handle potential false positives and provide robust attack confirmation, I suggest implementing a weighted voting system. Each detection method is assigned a confidence weight based on signal-to-noise characteristics:

- **Noether monitoring weight** (w_N): 0.6 – High specificity for physical-layer attacks
- **REDA statistical analysis weight** (w_R): 0.4 – Sensitive to statistical biases

The combined detection score is:

$$S_{\text{detect}} = w_N \cdot I_N + w_R \cdot I_R \tag{17}$$

Table 1: Attack Taxonomy via Symmetry Violations

Attack Type	**Bose-Einstein**	**Schrödinger**	**Heisenberg**	**Noether Violation**
Decoherence	Thermal photons	T_2 reduction	$\Delta x \Delta p$ increases	Energy non-conserved
Blinding	$g^{(2)} \to \infty$	Coherence $\to 0$	Classical regime	Photon # violated
PNS	Multi-photon	—	—	Photon # changed
Pulse Morph	—	Phase modulation	—	Phase symmetry
Timing Skew	—	Time-dependent $\hat{H}$	$\Delta E \Delta t$	Time symmetry
Spatial-mode	—	—	$\Delta x \Delta p$	Momentum violation
Entanglement	Bell correlations	Non-local evol.	EPR paradox	Local unitarity
Trojan-horse	Back-reflected photons	—	—	Photon # violated

where $I_N, I_R \in \{0, 1\}$ are binary indicators for Noether and REDA anomalies, respectively.

Decision threshold: An attack is confirmed if:

$$S_{\text{detect}} \geq \theta_{\text{conf}} = 0.6 \tag{18}$$

This ensures that:

- Both methods flagging ($I_N = I_R = 1$) give $S = 1.0$ (definite attack)
- Noether alone ($I_N = 1, I_R = 0$) gives $S = 0.6$ (confirmed attack)
- REDA alone ($I_N = 0, I_R = 1$) gives $S = 0.4$ (warning, requires investigation)

False positive mitigation: For REDA-only detections ($S < 0.6$), the system triggers enhanced monitoring with reduced detection thresholds for 10 seconds. If Noether violations emerge during this period, the attack is retroactively confirmed. This two-stage approach reduces false positive rates while maintaining high sensitivity.

4.4 Integration with Classical Security Infrastructure

While this framework focuses on physical-layer attacks, a complete security posture requires integration with classical intrusion detection systems (IDS). I propose a layered architecture:

Layer 1 – Physical (Noether/REDA): Monitors quantum channel and detector behavior for symmetry violations and statistical anomalies. Detects: detector blinding, PNS attacks, decoherence shaping, timing attacks.

Layer 2 - Protocol (Classical IDS): Monitors classical communication channels for:

- Basis reconciliation anomalies
- Privacy amplification side-channels
- Authentication protocol attacks

- Denial-of-service attempts

Layer 3 - Information-Theoretic: Post-processing analysis for:

- Mutual information leakage ($I(A:E) > \epsilon$)
- Error rate deviations from quantum predictions
- Min-entropy deficits in final keys

Cross-layer correlation engine: A correlation module integrates alerts across layers. For example:

- Noether violation (photon number) + elevated classical traffic → PNS attack with intercept-resend
- REDA anomaly + basis reconciliation delays → Man-in-the-middle with quantum channel manipulation
- No physical anomaly + protocol deviations → Pure information-theoretic attack

This integration addresses the limitation noted in Section 7: pure information-theoretic attacks without physical manifestations are caught by Layer 2/3, while physical attacks are detected by Layer 1. The correlation engine provides attack attribution and recommended countermeasures.

Standardization pathway: I propose that commercial QKD systems implement:

1. Mandatory Noether monitoring for all four fundamental symmetries
2. REDA statistical analysis with $> 10^6$ sample baselines
3. Classical IDS integration via standardized alert format (e.g., STIX 2.1)
4. Cross-layer correlation with automated countermeasure deployment

5 Physical Bounds and Feasibility Analysis

Jackson's semiconductor physics defines exploit feasibility regions:

5.1 Detector Blinding Threshold

From Eq. (12), for typical SPADs with $V_{\text{junction}} \sim 10^{-12}$ cm^3, photon energy $E_{\text{photon}} \sim 0.8$ eV (at 1550 nm), avalanche buildup time $\tau \sim 10^{-9}$ s, and quantum efficiency $\eta \sim 0.1$:

$$P_{\text{sat}} \approx \frac{10^{18}\,\text{cm}^{-3} \times 10^{-12}\,\text{cm}^3 \times 0.8\,\text{eV}}{0.1 \times 10^{-9}\,\text{s}} \approx 10\text{–}50\,\mu\text{W} \tag{19}$$

consistent with experimentally reported blinding thresholds [4]. Attacks requiring $P > 50$ μW are feasible; those requiring $P > 10$ mW face thermal and damage constraints.

5.2 Wavelength Attack Window

For silicon detectors, $\eta(\lambda)$ varies from $\sim$0.9 at 850 nm to $\sim$0.1 at 1550 nm. This 9$\times$ efficiency variation enables spectral basis biasing with high effectiveness.

5.3 Temporal Precision Requirements

Carrier transit time sets the ultimate timing resolution $\sim$10 ps. Attacks requiring $\Delta t < 10$ ps are physically infeasible with current detector technology.

6 Experimental Validation

I validate the framework against documented attacks:

Decoherence Shaping (Eq. 4): Using $T_2 = 1\ \mu$s (natural), $\gamma_{\text{adv}} = 10^7\ \text{s}^{-1}$, $\varepsilon_{\text{env}} = 0.5$, at $t = 100$ ns:

$$T_2' = 1 \times e^{-10^7 \times 0.5 \times 10^{-7}} \approx 0.61\,\mu\text{s} \tag{20}$$

Entropy reduction: $\Delta H \approx 1.0 \times \log_2(1/0.61) \approx 0.71$ bits.

Noether detection: The effective adversarial decoherence rate $\gamma_{\text{adv}} \cdot \varepsilon_{\text{env}} = 5 \times 10^6\ \text{s}^{-1}$ exceeds the natural decoherence rate $1/T_2 = 10^6\ \text{s}^{-1}$ by a factor of five, producing a measurable drift in the energy expectation $\langle \hat{H} \rangle$ of the probe state that is detectable within the 3σ monitoring window of Algorithm 1 over a typical $\sim 10^4$-pulse integration interval.

Photon-Number Splitting: For $\langle n \rangle = 0.1$ (weak coherent pulse), the Poissonian multi-photon probability is $P(n \geq 2) = 1 - e^{-0.1}(1 + 0.1) \approx 4.7 \times 10^{-3}$. Under the canonical PNS attack Eve removes one photon from each multi-photon pulse, so:

$$\Delta\langle \hat{N} \rangle_{\text{per pulse}} = \langle \hat{N} \rangle_{\text{in}} - \langle \hat{N} \rangle_{\text{out}} \approx P(n \geq 2) \approx 4.7 \times 10^{-3} \tag{21}$$

Over 10^6 pulses: $\Delta N \approx 4700$ photons removed, well above the Poisson shot-noise floor $\sqrt{\mu \cdot 10^6} \approx 316$, confirming easy detectability of photon-number non-conservation.

7 Discussion and Future Work

This unified framework transforms quantum cryptanalysis from heuristic vulnerability discovery to systematic, physics-grounded security analysis. Key contributions:

1. **Mathematical completeness:** Noether's theorem guarantees that all physical attacks violate at least one symmetry.
2. **Predictive power:** The framework enables a priori attack surface characterization before implementation.
3. **Practical detection:** Conserved quantity monitoring provides comprehensive, real-time attack detection.
4. **Physical bounds:** Jackson's semiconductor physics quantifies feasible regions for attacks.
5. **Layered security:** Integration with classical IDS provides defence-in-depth against hybrid attacks.

Limitations: While the enhanced framework now addresses integration with classical security systems, challenges remain in:

- Computational overhead of continuous symmetry monitoring at Gbps data rates
- Calibration drift in long-term deployments requires adaptive thresholds
- Quantum attacks exploit measurement-induced decoherence (requiring refined symmetry analysis)

Future directions:

- **Noether security proofs:** Develop formal security proofs based on symmetry preservation rather than information-theoretic bounds.
- **Continuous-variable QKD:** Extend the framework to Gaussian states and homodyne detection.
- **Relativistic effects:** Incorporate general relativity into satellite-based QKD.

- **Standardization:** Propose Noether monitoring as a certification requirement for commercial QKD systems, potentially through ETSI or ITU-T standards bodies.

- **Machine learning integration:** Train neural networks on symmetry violation patterns for rapid attack classification.

8 Conclusion

By synthesizing Bose-Einstein statistics, Schrödinger evolution, Heisenberg uncertainty, Noether's symmetries, Jackson's material physics, and Dirac's formalism, we establish that quantum security is fundamentally a question of symmetry preservation. Every attack is a symmetry violation; every violation is detectable. This framework provides both theoretical completeness and practical methodology, honouring the legacy of Emmy Noether by applying her profound insights to secure the quantum information age.

The integration with classical security infrastructure and enhanced voting algorithms transforms this from a theoretical framework into a deployable security architecture. The weaponization of quantum phenomena is inevitable. But armed with fundamental physics and layered defences, comprehensive detection is achievable.

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