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Deterministic Entanglement as a Prerequisite for Scalable Quantum Photonic Resource State Generation

Yorick Reum¹ | Matteo Santandrea² | Rohit Prasad¹ | Raphael Weber^{2,3} | Jonathan J. Finley⁴ | Tobias Huber-Loyola^{1,5} | Andreas Theo Pfenning¹  | Stefanie Barz⁶ | Sven Höfling¹

¹Julius-Maximilians-Universität Würzburg, Technische Physik, Physikalisches Institut and Würzburg-Dresden Cluster of Excellence ctd.qmat, Am Hubland, Würzburg, Germany | ²QC Design GmbH, Ulm, Germany | ³Institute of Theoretical Physics & IQST, Ulm University, Ulm, Germany | ⁴Walter Schottky Institut, Physics Department, School of Natural Sciences, MCQST, Technische Universität München, Garching, Germany | ⁵Institute of Photonics and Quantum Electronics & IQST, Karlsruhe Institute of Technology, Karlsruhe, Germany | ⁶Institute for Functional Matter and Quantum Technologies & IQST, University of Stuttgart, Stuttgart, Germany

Correspondence: Yorick Reum (yorick.reum@uni-wuerzburg.de) | Andreas Theo Pfenning (andreas.pfenning@uni-wuerzburg.de) | Sven Höfling (sven.hoeffling@uni-wuerzburg.de)

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ABSTRACT

As demonstrated experimentally by Prevedel et al., active feed-forward can render one-way quantum computation deterministic. An analogous principle applies to the scalable generation of photonic resource states: because each probabilistic photonic fusion operation branches the construction process, the overall success probability shrinks exponentially unless entanglement is generated deterministically. A simple comparative combinatorial resource estimate illustrates the practical consequences of this principle. State-of-the-art fault-tolerant optical quantum computing architectures incur an unreasonably high single-photon overhead when relying solely on probabilistic fusion. In contrast, deterministic sources of entangled multi-photon states, such as semiconductor quantum dots, can reduce the number of required attempts dramatically. Assuming realistic system efficiencies, on average only 15 attempts are needed to generate a 4-qubit resource state (4-star), and 89 attempts for a 6-qubit state (6-ring), bringing efficient resource state generation in reach with near-term photonic systems.

1 | Introduction

A central cornerstone of measurement-based quantum computation (MBQC) is that “active feed-forward of the classical measurement results renders one-way quantum computation deterministic” [1]. This principle captures a fundamental architectural constraint: probabilistic operations alone lead to exponentially branching computational paths, and only an active mechanism that compensates for this randomness restores determinism and efficiency.

The same structural limitation applies directly to any photonic quantum computing architecture that relies on the generation

of entangled resource states. Each probabilistic fusion operation introduces branching in the construction process, and without a deterministic entanglement mechanism, the overall success probability decays exponentially with the number of required fusions. This determinism requirement is therefore not a technical detail but a foundational condition for scalable photonic quantum computing.

Today, the transformative potential of quantum computing is evident, yet the optimal hardware required to realize its theoretical promise remains to be determined. Achieving fault tolerance in quantum computing marks a major milestone in computing technology [2]. It would enable sublinear-time

Yorick Reum and Matteo Santandrea contributed equally to this work.

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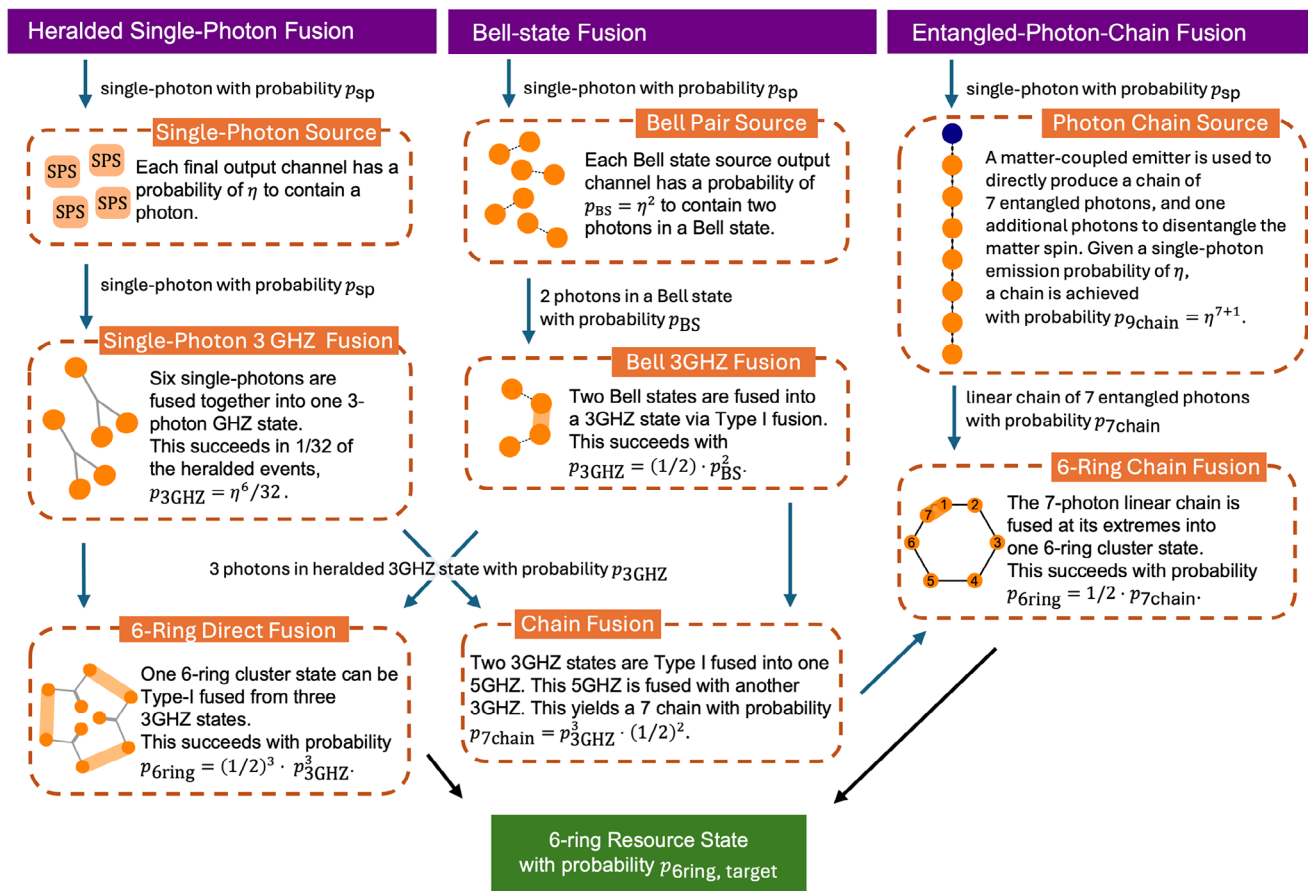


FIGURE 1 | Resource state generation protocols. As discussed in the main text, the resource states can be generated from seed states with different levels of entanglement. The intermediate states and their probabilities used for our calculations are shown in this figure for the 6-ring resource state (for the 4-star resource state, see [Supporting Information](#)).

searches of unstructured data [3, 4] and polynomial-time factoring of large numbers [5, 6], significantly expanding upon what is computationally feasible and having wide-ranging practical impact. Promising platforms include trapped atoms [7] or ions [8], superconducting qubits [9], solid-state systems [10, 11], and photons [12–14]. All current contenders still face engineering challenges that need to be overcome to achieve a universal or utility-scale quantum computer [15].

1.1 | Fusion-Based Quantum Computing

Photonic systems have special properties that need to be considered when designing quantum-computing architectures and systems. In particular, deterministic two-qubit gates would need a strong optical nonlinearity on the single-photon level, which is challenging to achieve [16, 17].

In this context, fusion-based quantum computation (FBQC), a recently proposed adaptation of measurement-based quantum computing (MBQC), has emerged as a model for fault-tolerant universal quantum computing, built upon the physical primitives readily available in photonic systems [16]: entangling measurements, known as fusions, performed on the qubits of constant-sized few-photon entangled resource states such as 4-star or 6-ring resource states, shown in the insets to Figure 1.

FBQC shifts the technological challenge of building a universal quantum computer to realizing a deterministic resource state generator, together with a fast feed-forward technology that can modify photonic states based on measurement results [18, 19].

The progress on the photonic architecture has been accompanied by tremendous progress in hardware and component development, made possible by the manufacturing capabilities of TIER 1 semiconductor production facilities [20]. However, it remains an open question which technology will best facilitate the generation of the required entangled resource states.

Here, we compare three scenarios that differ in complexity and capability, with resource states generated from:

- i. unentangled single photons,
- ii. Bell pairs, and
- iii. a 1D entangled-state source as proposed by Lindner and Rudolph [21].

1.2 | Scope and Purpose

This manuscript focuses on the architectural implications of deterministic versus probabilistic resource-state generation,

TABLE 1 | Comparison of different generation protocols in terms of the number of source states S , source photons M , and the probabilities P_{success} of successfully creating a 4-star or a 6-ring resource state, depending on the end-to-end efficiency η .

	4-star			6-ring		
	S	M	P_{success}	S	M	P_{success}
Unentangled single photons	8	8	$\eta^8 \cdot \frac{1}{128}$	18	18	$(\eta^6 \cdot \frac{1}{32})^3 \cdot (\frac{1}{2})^3$
Bell pairs	3	6	$\eta^6 \cdot (\frac{1}{2})^2$	6	12	$\eta^{12} \cdot (\frac{1}{2})^6$
1D entangled state	1	5	$\eta^{(4+1)}$	1	8	$\eta^{(7+1)} \cdot \frac{1}{2}$

rather than on system-specific imperfections or fault-tolerance thresholds. Our aim is to explicitly show the scaling behavior and physical resource requirements associated with different classes of photon sources, thereby informing the design space for measurement-based quantum computing. We do not attempt to model platform-dependent effects such as spectral mismatch, decoherence, or fabrication variability, nor do we derive new fault-tolerance thresholds. Instead, we isolate the structural role of deterministic entanglement generation as a prerequisite for scalable implementations of FBQC, independent of the specific emitter technology.

We use FBQC as our working example because it offers exceptionally favorable error thresholds. Additionally, it employs small, tangible, few-photon resource states that allow to illustrate the underlying scaling. This choice is didactical rather than fundamental. The same determinism requirement applies equally to MBQC architectures that start from large multi-photon cluster states: in both settings, probabilistic entanglement generation leads to exponential overheads, while deterministic generation restores scalability.

2 | Results: Success Probabilities, Loss Scaling, and Multiplexing Requirements

2.1 | Resource-State Generation Framework

We distinguish between source states and resource states. Source states are the elementary photonic states provided directly by the hardware, such as single photons, Bell pairs, or 1D cluster states. Resource states are the specific graph states required by MBQC. For FBQC these are namely the 4-star and 6-ring, which are assembled from source states via fusion operations. This separation makes it clear which requirements stem from the emitters and which arise from the architecture.

Fusion operations create entanglement through projective measurements that combine two photonic qubits and thereby can create larger graph states. In linear optics, these operations rely on two-photon interference and therefore succeed only probabilistically. The two standard variants are Type-I and Type-II fusions: Type-I consumes one photon from each input state, while Type-II consumes both photons. Both succeed with a maximum probability of $1/2$ [22], reflecting the absence of deterministic optical nonlinearities. (Note: boosting fusions to higher success probabilities is possible at the cost of additional ancilla photons [23–25]. These operations form the basic

mechanism by which small source states are assembled into the 4-star and 6-ring resource states used in FBQC. As a result, any architecture that relies solely on probabilistic fusions must contend with exponential branching in the construction process.

Photon loss is captured by the end-to-end efficiency η , which aggregates all loss contributions from the source, coupling, and optical components. We assume ideal photon-number-resolving detectors (close to the state of the art [26, 27]) and fidelity-preserving optical components to isolate the scaling behavior of resource-state generation. This allows us to focus on the structural consequences of probabilistic versus deterministic entanglement generation.

2.2 | Success Probability and Loss Scaling

We compare three classes of source states: unentangled single photons, Bell pairs and 1D entangled states (e.g., spin-photon cluster states). These are transformed via fusion operations into the resource states required for FBQC, the 4-star and 6-ring graph states. For each source-state class, we base our analysis on the best protocol known to us from the literature, ensuring that the comparison reflects the highest-efficiency strategy available for generating the resource states.

- i. **Unentangled Single Photons:** The 4-star state is equivalent to a 4-photon *Greenberger–Horne–Zeilinger* (4GHZ) state, up to local Clifford unitaries [28]. Via linear optics circuits consisting of Type-I and Type-II fusions, a heralded 4GHZ state can be generated with a probability of $\frac{1}{128}$ from 8 single photons [29, 30]. To create larger states, first a heralded 3GHZ seed state is created via fusion from six input photons. This is again an intrinsically probabilistic process with a success rate of $\frac{1}{32}$ [30–32]. Notably, photonic cluster states of arbitrary size can be generated (not necessarily optimally) via fusion gates that act on 3GHZ seed states [16, 17, 33, 34]. With this protocol, a 6-ring can be created from three 3GHZ states and three Type-I fusions.
- ii. **From Bell Pairs:** Likewise, three (six) Bell pairs and two (six) Type-I fusions can be used to create a 4-star (6-ring).
- iii. **From a 1D Entangled State Source:** When a charge spin of an emitter is used as an entangler of subsequently emitted photons, the 4-star can be created directly from the source (with the protocol we consider), whereas the 6-ring state requires an additional Type-I fusion step. The protocols require an

overhead of one photon for the disentanglement of the spin [21]. In the present work, we specifically consider high-rate single-photon emitting semiconductor quantum dots [35–37] as 1D entangled state sources. Similar spin-photon interfaces based on trapped atoms [38] or nitrogen-vacancy centers [39] may offer comparable advantages.

The protocols for the three different seed states are shown in Figure 1. We note that none of the protocols exploits feed-forward mechanisms during the resource state generations.

The following Table 1 summarizes the total number of input photons, M , and success probabilities to create a 4-star or 6-ring resource state for each strategy.

The impact of the initial entanglement provided by the source on the probability p_{success} of successfully creating the targeted resource state is self-evident. Considering an idealist case (no loss, $\eta = 1$), the 4-star can be directly and deterministically generated from a 1D entangled state source (that is, $p_{\text{success}} = 1$; up to local Clifford unitaries), with $p_{\text{success}} = 1/4$ when starting from Bell pairs, and with $p_{\text{success}} = 1/128$ when starting from unentangled single-photons. This difference of three orders of magnitude owes to the entanglement readily provided by the 1D entangled state. For the 6-ring, this difference increases considerably, to five orders of magnitude.

As photon loss is always present in real-world systems, we now consider the case with end-to-end efficiency $\eta < 1^{40}$. Figure 2a,b show p_{success} as a function of η for 4-star and 6-ring creation, respectively. Since $p_{\text{success}} \propto \eta^M$, where M is the number of input photons, resource state generation from 1D entangled state sources is the least affected by loss.

The highest experimental end-to-end efficiencies known are 57% (published in 2021) and 71.2% (published in 2025) with quantum dots embedded in open microcavities [40, 41]. For deterministic multi-photon entangled states from atoms, end-to-end efficiencies of up to 47.8% were shown [38].

For the highest demonstrated value of $\eta = 71.2\%$, we estimate the success probability of creating a 4-star (6-ring) from a 1D entangled state source to be $p_{\text{success}} = 18.3\%$ (3.3%), $p_{\text{success}} = 3.3\%$ ($2.7 \cdot 10^{-2}\%$) when starting from Bell pairs, and $p_{\text{success}} = 0.052\%$ ($8.4 \cdot 10^{-7}\%$) when using unentangled single-photons as a resource.

For emitters like atoms or quantum dots, the end-to-end efficiency is ultimately limited by the collection efficiency of the emitted photons. For spontaneous sources, the end-to-end efficiency can be approximated to be only limited by the probability of observing a single photon (photon number exactly equal to one) at the output of an individual source after the trigger event. This photon pair creation probability for such a case in heralded SPSs is limited to about 25% (above that, on average more than one photon is expected at the output port per heralding event) [42–44]. Values above 25% are therefore depicted as dashed lines in Figure 1 and can only be achieved using deterministic sources of entangled photon pairs [45], or via the use of single-photon storage [46, 47].

2.3 | Multiplexing Requirements

To build a quasi-deterministic generator emitting resource states with an arbitrarily high probability of p_{target} , one could multiplex a certain number of generation attempts, N . If p_{success} is the probability to succeed in a single attempt, then we have $(1 - p_{\text{success}})^N$ as the probability that after N attempts a specific multi-photon quantum state was *not* created successfully. The multiplexing analysis assumes that successful attempts can be identified from the detector outcomes of the underlying state-preparation/fusion circuit and selectively routed onward.

The number of required attempts for the generation of the state with a probability higher than p_{target} can then be calculated from $1 - (1 - p_{\text{success}})^N > p_{\text{target}}$ in the limit of equality, simply resulting in $N = \frac{\log(1-p_{\text{target}})}{\log(1-p_{\text{success}})}$. This number is shown in Figure 1c,d, where $p_{\text{target}} = 95\%$ is assumed as an (arbitrary) engineering benchmark. For $\eta = 71.2\%$, the number of attempts to create 6-ring (4-star) from a 1D entangled state is found to be only 89 (15). Even for the limit of $\eta = 100\%$, still over 10^3 (10^5) attempts are required to fuse a 4-star (6-ring) from unentangled single photons, compared to below 5 for fusion from a 1D entangled state source.

We emphasize that p_{success} is the fixed, protocol-intrinsic probability that a single execution yields the target state, whereas parallelization only increases the likelihood of obtaining at least one successful copy and does not modify the fundamental per-attempt probability.

Performing thousands of attempts to create a single resource state presents a significant engineering challenge, especially for the scaling of resource state generation rates, even with parallelized on-chip integrated spontaneous sources.

3 | Discussion and Practical Caveats

Our focus lies on the analysis of generation probabilities (rates) and the number of generation attempts to provide an estimate of the required resources. It is not possible to neglect that engineering challenges remain for all solid-state photon sources, especially achieving high quantum state fidelities. Efforts to tackle this include reduction of non-zero multi-photon probability $g^{(2)}(0)$, increasing of state fidelity by decoherence mitigation [48], improving optical components, and improving photon indistinguishability. Imperfect photon indistinguishability and non-unit source-state fidelity may also reduce the effective per-attempt generation probability. In linear-optical fusion-based protocols, this could be captured at first order through a reduced effective fusion success probability, although a complete treatment would also need to include the conditional fidelity of the final resource states. A further and deeper analysis of thresholds and a direct mapping between the tolerable physical imperfections of resource state generators and the fault-tolerance requirements is required to ultimately determine the most suitable technology for resource state generation.

The scalability of deterministic cluster-state sources ultimately depends on maintaining spin coherence and optical stability across many emission cycles. While rapid progress is being

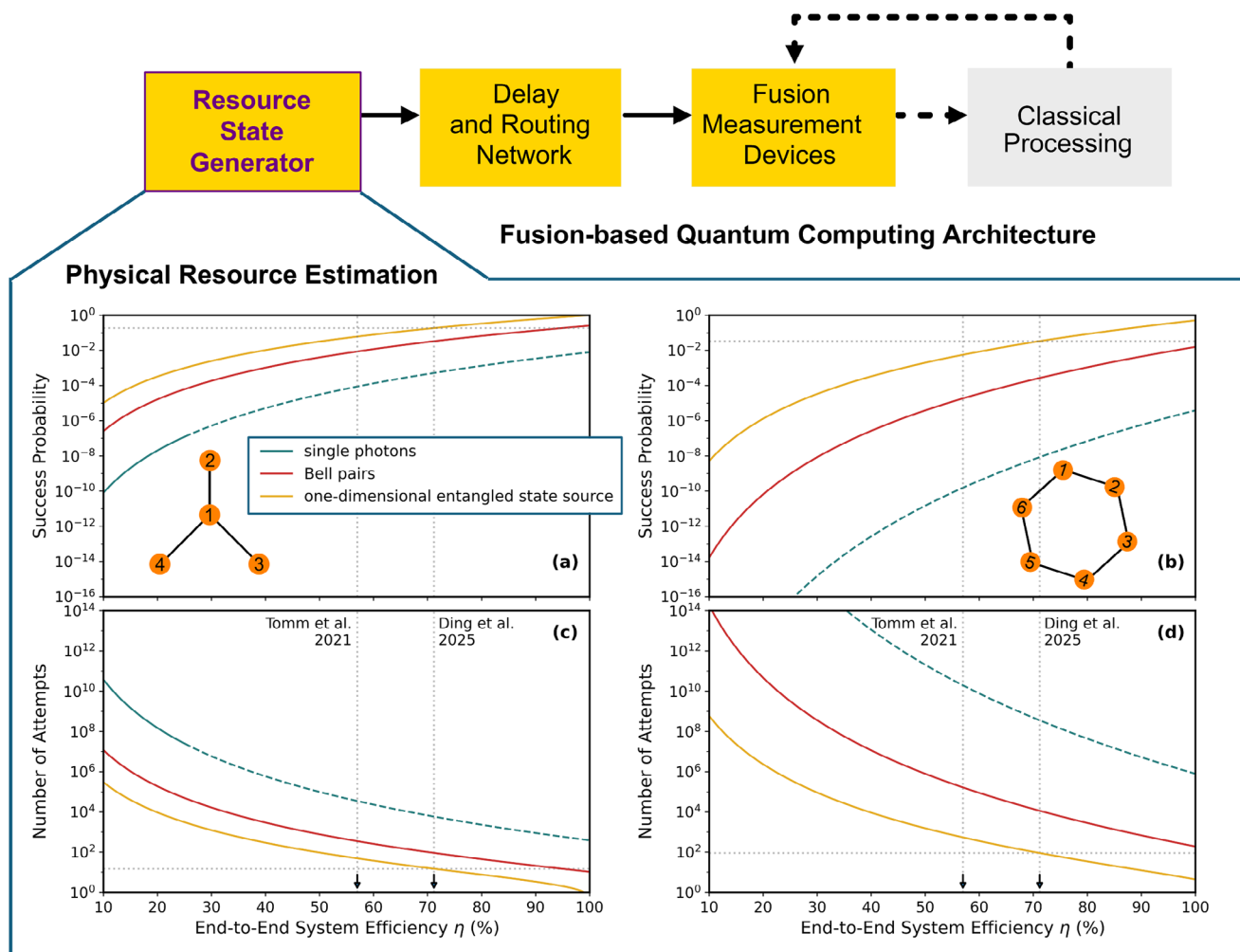


FIGURE 2 | Resource state generation efficiencies. Resource state generation is the initial and arguably most crucial task in measurement-based quantum computing. Resource states in the shape of a 4-star and 6-ring were proposed to form the fabric of the fusion-based quantum computing (FBQC) network, shown here in their graph representation. Each node of the graph is a qubit, e.g., the polarization mode of a single photon. Each edge of the graph corresponds to an entangling gate that was applied to the adjacent photons. The probability of successfully creating the resource state is plotted in (a) for the 4-star case, and in (b) for the 6-ring case as a function of the end-to-end system efficiency encapsulating the probabilities for creating, guiding, and detecting each photon. Three distinct strategies of resource state generation are discussed in detail in the main text and are shown here: starting with unentangled single photons; using Bell pairs as seed states; or employing deterministic sources of entangled multi-photon states driven with a suitable protocol. In (c) and (d) the number of generation attempts required to obtain one 4-star or 6-ring resource state with a probability of $p_{\text{target}} = 95\%$ is presented on a semi-log scale. Current state-of-the-art operation parameters for quantum dot single-photon sources are plotted as vertical dashed lines; the horizontal dashed line indicates the number of attempts needed for the highest end-to-end efficiency reported. The advantage for sources providing entangled seed states is apparent in all plots and manifests in a difference of multiple orders of magnitude in the required resources for state-of-the-art and optimal end-to-end system efficiencies.

made, long-chain cluster states remain sensitive to dephasing and spectral diffusion.

Resource-state fidelity, not just success probability, determines usefulness. The architectural advantages of deterministic sources assume that the generated resource states meet the fidelity thresholds required by the fusion-based protocol. Imperfections in photon indistinguishability, mode matching, and spin-photon entanglement fidelity reduce the effective utility of the generated states, even when the generation probability is high.

A complementary direction is to implement fusion operations using spin-photon gates rather than linear optics. Theoretical

proposals in cavity-QED systems have shown that spin-mediated photon-photon interactions can, in principle, enable deterministic or near-deterministic entangling operations, thereby avoiding the success-probability limit of linear-optical fusions. Examples include atom-photon gate schemes in optical cavities [49, 50] and analogous proposals for charged quantum dots in microcavities [51]. These approaches introduce additional coherence and control requirements, and high-fidelity experimental realizations remain challenging. Nevertheless, they illustrate that deterministic fusion could also be achieved at the gate level, reinforcing the architectural conclusion that deterministic entanglement generation (whether at the source or via deterministic gates) removes the exponential overheads inherent to probabilistic fusion. While

deterministic spin–photon gates offer a conceptually appealing route to high-efficiency fusion, current demonstrations remain limited to proof-of-principle regimes, and gate fidelities are not yet sufficient for large-scale resource-state assembly [52].

System-level considerations such as feed-forward latency, switching times, and real-time control are important for full-stack implementations but lie beyond the scope of this work. Our architectural conclusions assume that feed-forward operations (detection, processing, and switching) can be performed within the temporal budget set by the photon repetition rate. Achieving this in practice requires continued advances in integrated photonics and fast optical switching.

Deterministic generation addresses the exponential overhead associated with probabilistic fusion. Our analysis presents a first step in this direction, enabling an initial benchmarking of several competing approaches for resource state generation using comparable metrics.

4 | Conclusion

In summary, the central insight that active feed-forward renders one-way quantum computation deterministic finds a direct architectural analogue in the generation of photonic resource states. Our analysis shows that the same structural principle applies, that is, probabilistic operations inevitably lead to exponential overheads, whereas deterministic entanglement generation collapses this branching and restores scalability.

Single photon sources capable of emitting 1D chains of entangled photons (such as semiconductor quantum dots, trapped atoms, and color centers) embody this determinism when operated in the Lindner–Rudolph protocol. In this mode of operation, each optical excitation produces a photon with near-unit probability, representing deterministic photon emission, and each emission event extends the 1D cluster state with unit probability, representing deterministic entanglement growth. By providing both photons and entanglement on demand, these sources eliminate the orders-of-magnitude resource penalties inherent to probabilistic fusion-based strategies and enable high-rate generation of complex resource states with dramatically reduced physical overhead.

Although technical challenges remain, rapid progress in solid-state emitters, optical components, and system efficiencies indicates that deterministic multi-photon sources are approaching the performance thresholds required by fusion-based quantum-computing architectures. These advancements position them as practical candidates for near-term, scalable implementations of photonic quantum computing.

Author Contributions

S.H. conceived the project. M.S., Y.R., R.P., R.W., and A.T.P. developed the theoretical framework and carried out the analysis. J.J.F., S.B., A.T.P., T.H.-L., and S.H. supervised the work and critically validated the analysis. Y.R. and A.T.P. wrote the manuscript with input from all authors. S.B. and S.H. further provided experimental expertise and literature

insights that guided the project. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: qute70301-sup-0001-SuppMat.docx.