

Generation of Multi-Photon Entangled States via Stimulated Emission from Reflection-Symmetric Matter

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Abstract

Multi-photon entanglement constitutes a core technology for quantum communication and optical quantum computing. The currently prevalent entangled photon source relies on two-photon entanglement generated via spontaneous parametric down-conversion. Despite significant achievements, this approach remains far from satisfying the application demands of quantum computing, necessitating the exploration of novel pathways from both theoretical and experimental perspectives.

This work investigates the fundamental process and underlying mechanism of stimulated emission, revealing that the quantum properties of the initially produced two-photon state are intimately correlated with the symmetry of the emitting medium. If the electronic states of the gain medium possess parity, their wavefunctions also exhibit parity, as exemplified by atoms, molecules with a center of symmetry, and crystals featuring inversion symmetry. The electronic states of such materials inherently possess both parity and reflection symmetry. The stimulated emission process in parity-conserving materials adheres to parity conservation, yielding a two-photon state with parity that constitutes a superposition entangled state. Through the action of a parallel-plane resonator and subsequent stimulated emission, this process can be iteratively repeated, ultimately generating multi-photon entanglement.

The primary results and conclusions of this paper are as follows: stimulated emission from materials possessing parity generates multi-photon entangled states. If the electronic states of the laser gain medium exhibit parity, then the multi-photon state produced by stimulated emission within the laser resonator (parallel-plane cavity) is an entangled state, which can be extracted from a symmetric-structure bidirectional single-mode laser. The theory provides an expression for multi-photon entanglement. A symmetric-structure bidirectional-output single-mode He-Ne laser has been developed, and experimental verifica-

tion of the multi-photon entangled state has been conducted, with experimental results consistent with theoretical predictions.

Full Text

Multiphoton Entangled States Generated by Stimulated Radiation of Substances with Reflection Symmetry

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Abstract

Multi-photon entanglement represents a core technology for quantum communication and optical quantum computing. While spontaneous parametric down-conversion has emerged as the predominant source of two-photon entanglement and has achieved remarkable progress, it remains far from meeting the demands of practical quantum computing applications. This necessitates exploration of novel approaches from both theoretical and experimental perspectives. This paper investigates the fundamental mechanism of stimulated radiation and reveals that the quantum properties of the initially generated two-photon state are intimately connected to the symmetry characteristics of the emitting medium. When the electronic states of the stimulated radiation material possess parity, their wavefunctions exhibit corresponding parity properties—this applies to atoms, molecules with symmetric centers, crystals with inversion symmetry, and similar systems. The stimulated radiation process in parity-conserving materials obeys parity conservation, producing two-photon states with definite parity that exist as superposition entangled states. Through repeated cycles of stimulated radiation within a parallel-plane resonator, such entangled photon pairs can be cascaded to generate multi-photon entangled states.

The principal results and conclusions are as follows: Stimulated radiation from parity-conserving materials generates multi-photon entangled states. When the electronic states of the laser medium possess parity, the multi-photon states produced by stimulated radiation within a laser resonator (parallel-plane cavity) constitute entangled states. Theoretical expressions for multi-photon entanglement can be derived from symmetric bidirectional single-mode laser theory. A symmetric-structure bidirectional output single-longitudinal-mode He-Ne laser was developed and employed for experimental verification of multi-photon entangled states, with experimental results in excellent agreement with theoretical predictions.

Keywords: stimulated radiation; multiphoton entanglement; bidirectional single-mode laser

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Photon qubits and inter-photon entanglement constitute the foundation and core technology of optical quantum communication and quantum computing. Their advantages include stable properties, strong resistance to quantum decoherence, ease of single-qubit manipulation, convenient detection, and room-temperature operation. China's "Micius" satellite has successfully demonstrated intercontinental quantum communication between Beijing and Vienna, as well as quantum teleportation over 300 miles between ground stations and the satellite [1], representing a major breakthrough. Quantum teleportation is a critical technology for combating quantum decoherence and holds significant implications for fault-tolerant quantum computing, demonstrating the substantial application prospects of optical quantum information technology. Currently, spontaneous parametric down-conversion serves as the universally employed entangled photon source, and combined with multi-photon interference techniques, enables precise manipulation of 20-30 entangled photons. However, this technology faces fundamental scalability challenges. Quantum computing requires manipulation of 50-200 qubits with multi-qubit entanglement, a demand far exceeding the capabilities of existing entangled photon sources. This necessitates exploration of new theoretical and technical approaches to achieve scalable multi-photon entangled light sources.

This paper proposes that atomic stimulated radiation can generate multi-photon entanglement, which can be extracted through a symmetric-structure bidirectional single-mode laser to obtain multi-photon entangled light sources. The theoretical foundation rests on the principle that multi-photon states produced by atomic stimulated radiation within a bidirectional laser's parallel-plane resonator constitute multi-photon entangled states. This technology offers facile scalability and provides a broad platform for developing entangled light sources across various wavelength bands.

2.1 Mechanism of Stimulated Radiation

Photon-matter interaction triggers stimulated radiation, producing two photons. The properties of this two-photon state are intimately related to the symmetry of the emitting material. If the material's electronic states possess parity, their wavefunctions also exhibit parity. Under reflection transformation of spatial coordinates (x, y, z) , the wavefunction transforms as:

$$\Phi(x, y, z) = \psi(-x, -y, -z) \pm \psi(x, y, z) \quad (2.1.2)$$

$$\hat{I}\Phi(x, y, z) = \pm\Phi(x, y, z)$$

where the "+" sign indicates even parity and the "-" sign indicates odd parity. Equation (2.1.1) represents the reflection transformation. Materials with parity exhibit reflection symmetry. Both spontaneous and stimulated radiation processes in such materials obey parity conservation laws and selection rules.

Spontaneous emission photon states possess parity, and stimulated radiation two-photon states also possess parity. Photon states with definite parity are quantum superposition states. Atoms, molecules with symmetric centers, crystals with inversion symmetry, and similar materials all have electronic states with parity and reflection symmetry. If a material's electronic states lack parity and reflection symmetry, its spontaneous and stimulated radiation photon states will be devoid of parity.

Stimulated radiation initiated by spontaneous emission photons automatically satisfies all conservation laws. Energy conservation dictates that newly emitted photons possess identical energy to the incident photon; momentum conservation requires identical momentum, direction, and phase; angular momentum conservation ensures identical polarization. Consequently, for materials lacking reflection symmetry and parity, stimulated radiation produces coherent photon pairs with identical polarization, direction, and phase—the process is coherent. In contrast, materials with reflection symmetry and parity generate two-photon states with definite parity that exist as quantum superposition states. The quantum properties of two-photon states from these two classes of materials are fundamentally different.

2.2 Atomic Stimulated Radiation Generating 2N-Photon Entangled States

Quantum mechanics has established that atomic systems possess reflection symmetry. Electronic states with definite energy exhibit parity. Spontaneously emitted photons from excited electronic states have parity—electric dipole radiation photons possess odd parity, while magnetic dipole radiation possesses even parity. Stimulated radiation initiated by spontaneous emission automatically satisfies energy, momentum, angular momentum, and parity conservation. The resulting two-photon states from stimulated radiation possess definite parity. The relationship between stimulated radiation and the parity state of incident spontaneous emission photons is crucial and requires first determining the parity of the single-photon state from spontaneous emission.

2.2.1 Atomic Spontaneous Emission Single-Photon States

Consider an atom as a two-level system:

[Figure 1: see original paper] Atomic two-level energy diagram

$E_2 - E_1 = \hbar\omega$ represents the excited state electron energy, where \hbar is the reduced Planck constant and ω is the photon frequency. J_2 denotes the angular momentum of the excited electronic state, J_1 the angular momentum of the lower level E_1 , and m the magnetic quantum number of J_2 .

Assuming an electric dipole transition between E_2 and E_1 , these levels possess opposite parity. Spontaneous emission involves parity change between E_2 and

E_1 , resulting in photons with odd parity. A single-photon state is completely determined by its momentum state, spin state, and parity.

The photon momentum state is:

$$|\eta\rangle = |P_x, P_y, P_z\rangle \quad (2.2.1)$$

where $|P_x, P_y, P_z\rangle$ represents the photon momentum (2.2.2) with $P = \hbar K$, and K is the photon wavevector.

The photon spin states are:

$$\begin{aligned} |R^+\rangle &= \frac{1}{\sqrt{2}}[|H\rangle + i|V\rangle] \\ |L^+\rangle &= \frac{1}{\sqrt{2}}[|H\rangle - i|V\rangle] \end{aligned} \quad (2.2.4)$$

where $|H\rangle$ denotes horizontal polarization and $|V\rangle$ vertical polarization. $|R^+\rangle$ represents right-circularly polarized photons with spin +1, where the spin direction aligns with the photon momentum. $|L^+\rangle$ represents left-circularly polarized photons with spin -1, with spin direction also aligned with momentum.

Spontaneous emission single-photon states possess odd parity. Let \hat{I} be the parity operator:

$$\hat{I}|\eta^-\rangle = |\eta^+\rangle, \quad \hat{I}|\eta^+\rangle = |\eta^-\rangle \quad (2.2.5)$$

$$\begin{aligned} \hat{I}|R^+\rangle &= |L^-\rangle; \quad \hat{I}|L^-\rangle = |R^+\rangle \\ \hat{I}|L^+\rangle &= |R^-\rangle; \quad \hat{I}|R^-\rangle = |L^+\rangle \end{aligned} \quad (2.2.6)$$

where $|R^-\rangle = R_y(\pi)|R^+\rangle$ and $|L^-\rangle = R_y(\pi)|L^+\rangle$, with $R_y(\pi)$ representing a 180-degree rotation about the y-axis of the measurement coordinate system.

The single-photon state from spontaneous emission of the E_2 electronic excited state is expressed as [2]:

$$\begin{aligned} |\Phi_1\rangle^+ &= \frac{1}{\sqrt{2}}[|\eta^+R^+\rangle - |\eta^-L^-\rangle], \quad \Delta J = J_2 - J_1 = +1 \\ |\Phi_1\rangle^- &= \frac{1}{\sqrt{2}}[|\eta^-R^-\rangle - |\eta^+L^+\rangle], \quad \Delta J = J_2 - J_1 = -1 \end{aligned} \quad (2.2.7)$$

Equation (2.2.7) can be simplified as:

$$\begin{aligned}
|\Phi_1\rangle^+ &= \frac{1}{\sqrt{2}}[|R_k\rangle - |L_{-k}\rangle] \\
|\Phi_1\rangle^- &= \frac{1}{\sqrt{2}}[|L_k\rangle - |R_{-k}\rangle] \quad (2.2.8)
\end{aligned}$$

with $\hat{I}|\Phi_1\rangle^+ = -|\Phi_1\rangle^+$ and $\hat{I}|\Phi_1\rangle^- = -|\Phi_1\rangle^-$, confirming the odd parity of the photon states.

2.2.2 Atomic Stimulated Radiation Generating 2N-Photon Entangled States

Stimulated radiation is initiated by the single-photon superposition state from spontaneous emission of the excited electronic state E_2 . The spontaneous emission single-photon superposition state is:

$$|\Phi_1\rangle^+ = \frac{1}{\sqrt{2}}[|R_k\rangle - |L_{-k}\rangle]$$

Without loss of generality, we can define the momentum direction of photon $|R_k\rangle$ as the Z-axis, making the momentum direction of photon $|L_{-k}\rangle$ the -Z direction. This single-photon superposition state has a 50% probability of emitting a $|R_k\rangle$ photon along the +Z direction, triggering stimulated radiation that produces two photons with identical momentum and spin states:

$$|R_k R_k\rangle \quad (2.2.9)$$

This result follows from energy, momentum, and angular momentum conservation in stimulated radiation.

The superposition state also has a 50% probability of emitting a $|L_{-k}\rangle$ photon along the -Z direction, triggering stimulated radiation that produces two photons with identical momentum and spin states:

$$|L_{-k} L_{-k}\rangle \quad (2.2.10)$$

States (2.2.9) and (2.2.10) are mutually reflection-symmetric, as illustrated below:

[Figure 2: see original paper] Two-photon states a) and b) produced by stimulated radiation induced by single-photon superposition state $|\Phi_1\rangle^+$ are mirror symmetrical to each other

Atomic stimulated radiation obeys parity conservation. Since E_2 and E_1 have opposite parity and the incident photon $|\Phi_1\rangle^+$ has odd parity, the two-photon state from stimulated radiation must have even parity. However, neither state

(2.2.9) nor (2.2.10) individually possesses definite parity. The unique two-photon state satisfying both angular momentum and parity conservation is the superposition of (2.2.9) and (2.2.10), expressed as:

$$|\Phi_2\rangle^+ = \frac{1}{\sqrt{2}}[|R_k R_k, 0\rangle + |0, L_{-k} L_{-k}\rangle] \quad (2.2.11)$$

During atomic stimulated radiation, photon-atom interaction induces photon-photon interaction. The two-photon superposition state (2.2.11) emerges from probability amplitude interference between the two component states, forming an inseparable global state. Mathematically, $|\Phi_2\rangle^+$ cannot be decomposed into a direct product of two single-photon states, i.e., it cannot be expressed as $[\alpha|R_k\rangle + \beta|L_{-k}\rangle] \otimes [\gamma|R_k\rangle + \delta|L_{-k}\rangle]$. This demonstrates that the two-photon state $|\Phi_2\rangle^+$ produced by atomic stimulated radiation is indeed a two-photon entangled state.

The total spin of two right-circularly polarized photons emitted along the +Z direction is 2, with zero orbital angular momentum, yielding total angular momentum $\mathcal{T}_z = 2\hbar$. Similarly, two left-circularly polarized photons emitted along the -Z direction have total spin 2, zero orbital angular momentum, and total angular momentum $\mathcal{T}_z = 2\hbar$, with zero total momentum. Equation (2.2.11) can be expressed as:

$$|\Phi_2\rangle^+ = \frac{1}{\sqrt{2}}[|kk, 0\rangle + |0, -k - k\rangle] \frac{1}{\sqrt{2}}[|R_k R_k, 0\rangle + |0, L_{-k} L_{-k}\rangle] \quad (2.2.12)$$

This representation shows that the two-photon entangled state is simultaneously entangled in both momentum and circular polarization. The state $|\Phi_2\rangle^+$ has spin angular momentum 2 and is spherically symmetric, with its two components being mutually reflection-symmetric:

$$|\Phi_2\rangle^+ = \frac{1}{\sqrt{2}}[|kk, 0\rangle + \hat{I}|kk, 0\rangle][|R_k R_k, 0\rangle + \hat{I}|R_k R_k, 0\rangle] \quad (2.2.13)$$

Similarly, for $\Delta J = -1$, the two-photon entangled state from atomic stimulated radiation is:

$$|\Phi_2\rangle^- = \frac{1}{\sqrt{2}}[|kk, 0\rangle + |0, -k - k\rangle][|L_k L_k, 0\rangle + |0, R_{-k} R_{-k}\rangle] \quad (2.2.14)$$

Applying laser technology and selecting atoms as the gain medium with a parallel-plane resonator, when the stimulated radiation amplification gain exceeds losses, the expected 2N-photon entangled state from stimulated radiation becomes:

$$|\Phi_{2N}\rangle^+ = \frac{1}{\sqrt{2}}[|2Nk, 0\rangle + |0, 2N(-k)\rangle] \frac{1}{\sqrt{2}}[|2NR_k, 0\rangle + |0, 2NL_{-k}\rangle] \quad (2.2.15)$$

$$|\Phi_{2N}\rangle^- = \frac{1}{\sqrt{2}}[|2Nk, 0\rangle + |0, 2N(-k)\rangle] \frac{1}{\sqrt{2}}[|2NL_k, 0\rangle + |0, 2NR_{-k}\rangle] \quad (2.2.16)$$

To test this theory, we redesigned a He-Ne laser (representative of all atomic lasers) satisfying the following conditions: (1) The laser must emit symmetrically along the Z-axis (laser axis) in two opposite directions, ensuring beam propagation parallel to the Z-axis. (2) The resonator must be a parallel-plane cavity for optimal directional selectivity, with both cavity mirrors having identical reflectivity (99.7%) and identical transmissivity (0.3%). (3) A short cavity length with low-power output design is adopted to achieve single-mode operation.

2.3 He-Ne Laser Energy Levels

[Figure 3: see original paper] He-Ne laser energy level diagram (schematic)

Figure 3 shows a schematic diagram. Conventional He-Ne lasers do not consider the parity of laser energy levels. In atomic quantum mechanics, N-electron states have definite energy, angular momentum, and parity. Taking the Ne atom as an example with 10 electrons, the ground state configuration is $\text{Ne}(1S^{22}S^{22}P^6)$. The Ne ground state $2S^{22}P^6$ ($1S_0$) has total spin zero, total orbital angular momentum zero, and total angular momentum zero. The superscript “0” indicates odd parity, while no superscript indicates even parity. The Ne excited state $3S_2[1]$ has even parity (no superscript “0”).

Electronic states with parity are necessarily quantum superposition states, expressible as:

$$\frac{1}{\sqrt{2}}[|3S_2[1]\rangle - \hat{I}|3S_2[1]\rangle] \quad \text{and} \quad \frac{1}{\sqrt{2}}[|2P_4[2]\rangle + \hat{I}|2P_4[2]\rangle]$$

where \hat{I} is the parity operator. Both $3S_2[1]$ and $2P_4[2]$ represent 8-electron states with one electron promoted from the ground state. Data references [3].

For the He-Ne laser transition $3S_2[1] \rightarrow 2P_4[2]$, population inversion occurs. Spontaneous emission from $3S_2[1]$ produces a single-photon quantum superposition state with odd parity. Conservation of angular momentum and parity uniquely determines its expression:

$$|\Phi_1\rangle = \frac{1}{\sqrt{2}}[|L_k\rangle - |R_{-k}\rangle] \quad (2.3.1)$$

This is illustrated in Figure 4.

[Figure 4: see original paper] Ne- $3S_2$ ^[1] spontaneous emission producing single-photon quantum superposition state

The single-photon superposition state (2.3.1), after resonator feedback, interacts with Ne $3S_2$ ^[1] atoms to trigger stimulated radiation, producing a two-photon entangled state. Angular momentum and parity conservation uniquely determine its expression:

$$|\Phi_2\rangle^- = \frac{1}{\sqrt{2}}[|2L_k, 0\rangle + |0, 2R_{-k}\rangle] \quad (2.3.2)$$

State (2.3.2) has even parity with total angular momentum $\mathcal{T}_z = -2\hbar$ (zero orbital angular momentum, thus representing total spin angular momentum). Due to electron-electron interactions and spin-orbit coupling in Ne atoms, (2.3.2) cannot be decomposed into a direct product of two independent single-photon states, confirming it as a two-photon entangled state.

The process of Ne atom stimulated radiation generating two-photon entangled states is shown in Figure 5.

[Figure 5: see original paper] Schematic diagram of stimulated radiation process producing two-photon entangled state, induced by Ne- $3S_2$ ^[1] spontaneous emission $|\Phi_1\rangle = \frac{1}{\sqrt{2}}[|L_k\rangle - |R_{-k}\rangle]$

After one resonator reflection, (2.3.2) transforms to:

$$|\Phi_2\rangle^+ = \frac{1}{\sqrt{2}}[|2R_k, 0\rangle + |0, 2L_{-k}\rangle] \quad (2.3.3)$$

This interacts with two Ne atoms in the $2P_4$ ^[2] state through stimulated absorption, entangling the two Ne atoms and promoting them to the $3S_2$ ^[1] state, where they become entangled in $3S_2$ ^[1]. After one round-trip through the resonator, (2.3.2) remains unchanged and triggers stimulated radiation from two entangled Ne atoms in $3S_2$ ^[1], producing four-photon entanglement:

$$|\Phi_4\rangle^- = \frac{1}{\sqrt{2}}[|4L_k, 0\rangle + |0, 4R_{-k}\rangle] \quad (2.3.4)$$

After resonator reflection, this transforms to:

$$|\Phi_4\rangle^+ = \frac{1}{\sqrt{2}}[|4R_k, 0\rangle + |0, 4L_{-k}\rangle] \quad (2.3.5)$$

Thus, the cycle proceeds: entangled photon stimulated absorption \rightarrow atomic entanglement \rightarrow entangled atom stimulated radiation \rightarrow 2N-photon entanglement.

This process continues to equilibrium—stable entangled light oscillation—when stimulated radiation gain exceeds losses. Macroscopic entangled photons and macroscopic entangled atoms within the resonator form a special quantum system. Both entangled photons and entangled atoms constitute Bose-condensed states (Ne atoms, as composite particles, are bosons). The two systems can simulate each other, enabling determination of entangled atom properties through entangled photon measurement. The entangled photon states within the resonator are:

$$|\Phi_{2N}\rangle^- = \frac{1}{\sqrt{2}}[|2NL_k, 0\rangle + |0, 2NR_{-k}\rangle] \quad (2.3.6)$$

$$|\Phi_{2N}\rangle^+ = \frac{1}{\sqrt{2}}[|2NR_k, 0\rangle + |0, 2NL_{-k}\rangle] \quad (2.3.7)$$

Superposition and interference of (2.3.6) and (2.3.7) within the resonator produce a new entangled state:

$$|\Phi_{2N}\rangle^0 = \frac{1}{\sqrt{2}}[|NR_k, NR_{-k}\rangle + |NL_k, NL_{-k}\rangle] \quad (2.3.8)$$

State $|\Phi_{2N}\rangle^0$ has even parity, total angular momentum $2N\hbar$, and zero total angular momentum component. In the H/V basis, (2.3.8) becomes:

$$|\Phi_{2N}^{HV}\rangle^0 = \frac{1}{\sqrt{2}}[|NH_k, NH_{-k}\rangle + |NV_k, NV_{-k}\rangle] \quad (2.3.9)$$

States (2.3.6) through (2.3.9) can be bidirectionally output from the resonator along the Z-axis (optical axis) in two opposite directions.

General single-photon polarization quantum superposition states ($\cos\theta|H\rangle + e^{i\phi}\sin\theta|V\rangle$) have infinite possible configurations. Reflection symmetry reduces this infinite parameter space (θ, ϕ) to $(\pi, 0)$. Many important quantum properties of macroscopic photon entangled states derive from this reflection symmetry. For instance, reflection symmetry leads to zero total momentum, making the momentum components of the entangled state perfectly correlated and the total momentum precisely defined. Reflection symmetry also renders the position difference between the two components completely determined, resulting in high position correlation. Similarly, time difference and phase difference between the two components are completely determined and highly correlated, while time, position, and phase themselves remain random.

2.4 Experimental Verification

2.4.1 Multi-Photon Entanglement Polarization Correlation Experiments

The experimental setup for bidirectional output laser multi-photon entangled states is shown in Figure 6.

[Figure 6: see original paper] Experimental setup of multi-photon entangled state of two-way output laser

Experiment 1: Circular polarization entanglement correlation detection

Theoretical prediction: $|\Phi_{2N}\rangle^- = \frac{1}{\sqrt{2}}[|2NL_k, 0\rangle + |0, 2NR_{-k}\rangle]$

The experimental configuration is shown in Figure 7.

[Figure 7: see original paper] Experimental settings for detection of polarization correlation of circular polarization entanglement

Here, S denotes the setup from Figure 6. The PL($\pi/2$)-QWP($5\pi/4$) combination in channel I detects $|2NL_k, 0\rangle$, while the PL(π)-QWP($-\pi/4$) combination in channel II detects $|0, 2NR_{-k}\rangle$.

Results: Coincidence measurements show energy output in channel I with zero output in channel II. After random delay, coincidence detection shows energy output in channel II with zero output in channel I. Subsequent random delay measurements detect simultaneous energy output in both channels I and II. Repeated experiments yield identical results, confirming theoretical predictions.

Experiment 2: Zero total spin circular polarization entanglement

Theoretical prediction: $|\Phi_{2N}\rangle^0 = \frac{1}{\sqrt{2}}[|NR_k, NR_{-k}\rangle + |NL_k, NL_{-k}\rangle]$

The experimental configuration is shown in Figure 8.

[Figure 8: see original paper] Experimental settings for detection of polarization correlation of circular polarization entanglement with zero total spin

The HWP($\pi/8$)-QWP(0) combination in channel I and HWP($-\pi/8$)-QWP(0) in channel II detect $|NR_k\rangle$ and $|NR_{-k}\rangle$, respectively. The HWP($\pi/8$)-QWP(0) combination in channel III and HWP($-\pi/8$)-QWP(0) in channel IV detect $|NL_k\rangle$ and $|NL_{-k}\rangle$, respectively. HWP denotes half-wave plate and QWP quarter-wave plate.

Results: I-II coincidence measurements detect simultaneous energy output in both directions with identical right-circular polarization, while III-IV outputs remain zero. After random delay, III-IV coincidence measurements detect simultaneous energy output with left-circular polarization, while I-II outputs become zero. Subsequent measurements detect simultaneous energy output in all four channels. Repeated experiments confirm these results, matching theoretical expectations.

Experiment 3: Linear polarization entanglement correlation detection

Theoretical prediction: $|\Phi_{2N}^{HV}\rangle^0 = \frac{1}{\sqrt{2}}[|NH_k, NH_{-k}\rangle + |NV_k, NV_{-k}\rangle]$

The experimental configuration is shown in Figure 9.

[Figure 9: see original paper] Experimental settings of polarization correlation detection for linear polarization entanglement

PBS denotes polarizing beam splitter.

Results: Coincidence measurements detect simultaneous energy output in channels I-II with zero output in III-IV. After random delay, III-IV show simultaneous output while I-II become zero. Subsequent measurements detect simultaneous output in all four channels. Repeated experiments confirm these results, consistent with theoretical predictions.

Experiment 4: Alternative circular polarization entanglement configuration

Theoretical prediction: $|\Phi_{2N}\rangle^+ = \frac{1}{\sqrt{2}}[|2NR_k, 0\rangle + |0, 2NL_{-k}\rangle]$

The experimental configuration is shown in Figure 10.

[Figure 10: see original paper] Experimental settings for detection of polarization correlation of circular polarization entanglement

The PL(0)-QWP($\pi/4$) combination in channel I detects $|2NR_k, 0\rangle$, while the PL($-\pi/2$)-QWP($-\pi/4$) combination in channel II detects $|0, 2NL_{-k}\rangle$.

Results: Coincidence measurements show energy output in channel I with zero output in channel II. After random delay, channel II shows output while channel I becomes zero. Subsequent measurements detect simultaneous output in both channels. Repeated experiments confirm these results, matching theoretical predictions.

In all four experiments, the detected signals are visible macroscopic beams. Thus, experimental confirmation has been achieved for four distinct multiphoton polarization entangled states.

3 Analysis and Discussion

The bidirectional output single-mode laser maintaining reflection symmetry has been experimentally verified as an entangled light source using the He-Ne bidirectional laser setup, with results consistent with theoretical predictions. Detection of quantum entanglement polarization correlations employed only linear optical elements: polarizers, polarizing beam splitters, half-wave plates, and quarter-wave plates.

When the electronic states of the laser medium possess parity (reflection symmetry), the laser generated through stimulated radiation amplification within the

laser resonator (parallel-plane cavity) constitutes entangled light. Symmetric-structure bidirectional single-mode lasers can output entangled light.

Atoms, ions, molecules with symmetric centers, and crystals with reflection symmetry all have electronic states with parity. Lasers constructed using these materials as gain media produce entangled light output when parity and other appropriate conditions are maintained. He-Ne lasers, argon ion lasers, CO₂ lasers, nitrogen molecular lasers, and crystal lasers with reflection symmetry all generate entangled light, provided the laser resonator contains no polarizing elements or other components that would destroy the intracavity entangled state.

Macroscopic-scale entangled light extends entanglement from two-photon to multi-photon (dozens of photons) and further to billions of photons, bridging the microscopic-to-macroscopic boundary. Macroscopic entangled light holds promise for quantum spectral imaging and long-distance target detection with ultra-high resolution and extremely low background noise, representing a worthwhile research direction. The decoherence properties of macroscopic-scale entangled light require further investigation.

References [1] Gabriel Popkin. China's quantum satellite achieves 'spooky action' at record distance. *Science*, 2017-6-15. <https://www.sciencemag.org/news/2017/06/chinas-quantum-satellite-achieves-spooky-action-record-distance> [2] Richard P. Feynman, Robert B. Leighton, Matthew Sands. *The Feynman Lectures on Physics*, The New Millennium Edition, Volume 3. Taipei: Global Views – Commonwealth Publishing Group, 2016: 18, P164. [3] A.A. Radzig, B.M. Smirnov. *Reference Data on Atoms, Molecules, and Ions*. Chemical Physics 31, P188-189.

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