Quantum total reflection of single-photon in imaging

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Research Article

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barrier; laser detection

This work theoretically considers the quantum tunneling effect on total reflection of single-photon with frequency ν in single-photon imaging. We find 1) that there exists a critical potential barrier V_c (in unit J) , above which total reflection definitely occurs, for the photon in a square barrier with arbitrary width and 2) that the critical barrier has a linear relationship with the frequency of lights from infrared to ultraviolet:

$$V_c = h\nu + 1.113437609582533e-20$$

where h is the Planck constant and $V_0 = 1.113437609582533e-20$ J is defined as the quantum total reflection constant of single-photon. This relationship could be used to choose light for practical single-photon imaging and laser detecting techniques.

Single-photon imaging has advantages both in small, light and low-power physical lidar systems¹⁻⁵ and in excellent single-photon sensitivity and time resolution of imaging processing⁶⁻⁸. This kind of technique includes physical parts such as single-photon detectors and arrays⁹ and the software parts processing with different algorithms^{10,11}, and yields a great number of positive results. For instance, in Ref [12], the best long-range of 3D single-imaging achieves 45km. Right now, how to further improve the accuracy of single-photon imaging is a frontier question in this field. To at least partly solve the problem, a proposed hypothesis is that there exists a total reflection of a single-photon from any object in nature in quantum level; that is, the single-photon detector will theoretically receive 100% of photons emitted from photon generator. The aim of present work is to evaluate the reflection efficient of single-photons using quantum mechanism. The following will study the property of quantum tunneling effect

on the total reflection of photons⁹.

The critical barrier V_c of each frequency ν is calculated with equation (7) (see in Method section) and determined by analyzing both the D-V-a (Fig. 1a) and R-V-a (Fig. 1b) spaces. For single-photon with $\nu=15*10^{14}\text{Hz}$, we find its V_c is 6.3002eV (Fig. 1c). Using this equation, we give all V_c from infrared ray to ultraviolet light (Table 1).

(Figure 1 and Table 1 are about here.)

Relationship between V_c and frequency ν is given by plotting all points in Table 1 into one figure (Figure 2). Using the first-order linear fitting method, we find

$$V_c = 6.622114444613997e-34\nu + 1.113437609582533e-20 \quad (1)$$

Comparing these numbers with physical constants in textbook⁹, we get

$$V_c = h\nu + 1.113437609582533e-20 \quad (2)$$

where h is the Planck constant and $V_0 = 1.113437609582533e-20 \text{ J}$ is defined as the quantum total reflection constant of single-photon.

(Figure 2 is about here.)

Quantum total reflection relationship (equation (2)) can be used to choose light for specific detection purpose^{4,13}. For instance, if we know the minimal potential barrier for a group of objects, $V = \min\{V_1, V_2, \dots, V_n\}$, then we can use the light with vibrational frequency

$$\nu = \frac{V - 1.113437609582533e-20}{h}, \quad (3)$$

by rewriting equation (2), in the single-photon camera. This light will have a 100% reflection of single-photon from the objects theoretically. This condition for choosing light could also be used in the laser detecting techniques, since laser is a group of

integrated single-photons¹⁴.

This work theoretically considers the quantum tunneling effect on total reflection of single-photon in an arbitrary square barrier and find that there exists a critical voltage for each light. Further, we find that the critical barriers have a linear relationship with the frequencies of lights from infrared to ultraviolet. The new relationship could be used to choose light for practical single-photon imaging, possible as well as other laser detections.

Methods

(Figure 3 is about here.)

The single-photon imaging involves several parts of physical systems, but here only covers the photon itself and the object the photon meets. This paper tries to partly solve the question set up in introduction. Consider a simple model: a single photon with $E=hf$ reflecting from a square potential barrier¹⁵⁻¹⁷. The barrier height is in the form of

$$V = \begin{cases} V & 0 < x < a \\ 0 & x < 0, x > a \end{cases} . \quad (4)$$

The transmission coefficient D and reflection coefficient R of this single-photon are given by

$$\begin{aligned} D &= \frac{4k_1^2 k_2^2}{(k_1^2 - k_2^2)^2 \sin^2 k_2 a + 4k_1^2 k_2^2} \\ R &= \frac{(k_1^2 - k_2^2)^2 \sin^2 k_2 a}{(k_1^2 - k_2^2)^2 \sin^2 k_2 a + 4k_1^2 k_2^2} \end{aligned} \quad \text{if } E > V ; \quad (5)$$

or

$$\begin{aligned} D &= \frac{4k_1^2 k_3^2}{(k_1^2 + k_3^2)^2 \sinh^2 k_2 a + 4k_1^2 k_3^2} \\ R &= \frac{(k_1^2 + k_3^2)^2 \sinh^2 k_2 a}{(k_1^2 + k_3^2)^2 \sinh^2 k_2 a + 4k_1^2 k_3^2} \end{aligned} \quad \text{if } E < V \quad (6)$$

where $k_1^2 = 2\mu E / \hbar^2$, $k_2^2 = 2\mu(E - V) / \hbar^2$, $k_3^2 = 2\mu(V - E) / \hbar^2$, $\mu = 4\pi \times 10^{-7} N / A^2$, and $\hbar = 1.054571726 \times 10^{-34} J \cdot s$. And $D + R = 1$. The transmission from left to right is just the tunneling effect in quantum mechanism ⁹ .

Aiming to get a clear image, we would expect a total reflection of single-photon from the object from the point of view of quantum mechanism. In this case, here defines a critical barrier V_c which follows

$$R(\%) = \begin{cases} 100 & [V_c, \infty) \\ [0, 100) & [0, V_c) \end{cases} \quad \text{for } \forall a \quad , \quad (7)$$

where 100 means total reflection of single-photon above V_c . This definition obviously includes both $E < V$ and $E > V$ cases above. Since the barrier width a is randomly chosen, this model possibly represents any arbitrary object in nature.

Author contributions

Y.J. designed the project, drawn the figures, and wrote the paper.

Competing financial interests: declared none.

References

1. Bruschini, C., Homulle, H., Antolovic, I. M., Burri, S. & Charbon, E. Single-photon avalanche diode imagers in biophotonics: review and outlook. *Light: Science & Applications* **8**, 87 (2019).
2. Hadfield, R. H. Single-photon detectors for optical quantum information applications. *Nature Photonics* **3**, 696–705 (2009).

3. Pawlikowska, A. M., Halimi, A., Lamb, R. A. & Buller, G. S. Single-photon three-dimensional imaging at up to 10 kilometers range. *Opt. Express* **25**, 11919–11931 (2017).
4. Li, H. *et al.* Superconducting nanowire single photon detector at 532 nm and demonstration in satellite laser ranging. *Opt. Express* **24**, 3535–3542 (2016).
5. Tobin, R. *et al.* Three-dimensional single-photon imaging through obscurants. *Opt. Express* **27**, 4590–4611 (2019).
6. Chan, S. *et al.* Long-range depth imaging using a single-photon detector array and non-local data fusion. *Scientific Reports* **9**, 8075 (2019).
7. Y. Altmann, X. Ren, A. McCarthy, G. S. Buller & S. McLaughlin. Lidar Waveform-Based Analysis of Depth Images Constructed Using Sparse Single-Photon Data. *IEEE Transactions on Image Processing* **25**, 1935–1946 (2016).
8. J. A. Richardson, L. A. Grant & R. K. Henderson. Low Dark Count Single-Photon Avalanche Diode Structure Compatible With Standard Nanometer Scale CMOS Technology. *IEEE Photonics Technology Letters* **21**, 1020–1022 (2009).
9. Razavy, M. *Quantum Theory of Tunneling*. (WORLD SCIENTIFIC, 2003). doi:10.1142/4984.
10. Kirmani, A. *et al.* First-Photon Imaging. *Science* **343**, 58 (2014).
11. Altmann, Y. *et al.* Quantum-inspired computational imaging. *Science* **361**, eaat2298 (2018).
12. Zheng-Ping Li, Xin Huang, Yuan Cao, Bin Wang, Yu-Huai Li, Weijie Jin, Chao Yu, Jun Zhang, Qiang Zhang, Cheng-Zhi Peng, Feihu Xu, Jian-Wei Pan. Single-photon

- computational 3D imaging at 45 km. *Photonics Research* **8**, (2020).
13. Xue, L. *et al.* Satellite laser ranging using superconducting nanowire single-photon detectors at 1064 nm wavelength. *Opt. Lett.* **41**, 3848–3851 (2016).
14. A. Einstein. Concerning an Heuristic Point of View Toward the Emission and Transformation of Light. *Ann. Phys.* **17**, 132 (1905).
15. Gamow, G. A. Zur Quantentheorie des Atomkerns. *Ztschrift für Physik A Hadrons and Nucl* **51**, 204–212 (1928).
16. Condon, Edw. U. & Gurney, R. W. Wave Mechanics and Radioactive Disintegration. (1991).
17. E. Schrödinger. Quantisierung als Eigenwertproblem. *Annalen der Physik* **385**, 361–376 (1926).

Table and Figure captions

Table 1. Predicted critical barrier V_c (in unit eV) for single-photon with frequency ν
(in unit 10^{14}Hz)

Figure 1. Plots of D-V-a (a), R-V-a (b) and vertical view of b (c) for a single-photon
with $\nu=15*10^{14}$ Hz. Above $V_c= 6.3002\text{eV}$ ($1\text{eV}= 1.6021766208*10^{-19}\text{J}$), R is 100%
(yellow in b and c), meaning total reflection of the single-photon.

Figure 2. Fitted linear relationship between V_c and frequency ν for single-photons

Figure 3. A single photon with $E=h\nu$ reflecting from a square potential barrier.

152 Table 1. Predicted critical barrier V_c (in unit eV) for single-photon with frequency ν
153 (in unit 10^{14}Hz)

ν	0.3	0.5	1	2	5	10
V_c	2.0000000E-01	3.0000000E-01	5.0000000E-01	9.0002562E-01	2.1000000E+00	4.1999739E+00
ν	12	15	17	20	30	40
V_c	5.0000000E+00	6.3001793E+00	7.1000000E+00	8.2999588E+00	1.2500000E+01	1.6600000E+01
ν	50	60	70	80	90	100
V_c	2.0700000E+01	2.4900000E+01	2.9000000E+01	3.3100000E+01	3.7300000E+01	4.1400000E+01

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Figure 1. Plots of D - V - a (a), R - V - a (b) and vertical view of b (c) for a single-photon with $\nu=15 \times 10^{14}$ Hz. Above $V_c=6.3002\text{eV}$ ($1\text{eV}=1.6021766208 \times 10^{-19}\text{J}$), R is 100% (yellow in b and c), meaning total reflection of the single-photon.

Figure 2. Fitted linear relationship between V_c and frequency ν for single-photons

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163 Figure 3. A single photon with $E = h\nu$ reflecting from a square potential barrier.

Figures

Figure 1

Plots of D - V - a (a), R - V - a (b) and vertical view of b (c) for a single-photon with $\nu=15 \cdot 10^{14}$ Hz. Above $V_c=6.3002\text{eV}$ ($1\text{eV}= 1.6021766208 \cdot 10^{-19}\text{J}$), R is 100% (yellow in b and c), meaning total reflection of the single-photon.

Figure 2

Fitted linear relationship between V_c and frequency ν for single-photons

Figure 3

A single photon with $E=hf$ reflecting from a square potential barrier.