

Quantum imaging with positronium-decay-emitted gamma rays

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The use of entangled gamma rays from positronium decay for quantum-enhanced imaging of dense materials is demonstrated. Quantum ghost images, where only one of the entangled 511-keV photons interacts with the object, are obtained for tantalum samples of varying density using a 210-ps time-resolution dual detector system and a Na-22 positron source. An analysis comparing both classical and quantum imaging modalities is employed to isolate true 511-keV events from background noise. Image quality is quantitatively assessed using transmission ratios and the Michelson contrast. Quantum-correlated images are found to exhibit superior (up to approximately 1.7x, from 0.49 to 0.83 in the thickest sample measured) contrast compared to classical methods and align well with theoretical expectations. These results suggest that quantum ghost imaging with positronium-based entangled gamma rays could significantly enhance noninvasive imaging of high-density objects, with potential applications in areas such as cargo inspection and security screening.

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I. INTRODUCTION

Positronium decay is a quantum process during which a bound state of an electron (e^-) and a positron (e^+) annihilates into two 511-keV gamma-ray photons. These photons are emitted in diametrically opposing directions due to the conservation of momentum and are, by definition, quantum entangled [1,2]. This annihilation process is most known for its application in positron emission tomography (PET), a medical diagnostic tool where positron-emitting radiotracers collect in metabolically active tissue, such as tumors, and the emitted photons are back-projected to estimate their point of origin [3,4]. Beyond medical diagnostics, an important

application of gamma rays is in gamma-ray radiography, a noninvasive imaging technique used to visualize the internal structure of objects without physical access. It is widely used in fields such as industrial inspection, aerospace, and homeland security [5].

Entangled annihilation gammas have unique physical properties that can be exploited in quantum imaging setups to improve the signal-to-noise ratio (SNR) of these gamma-ray radiography images, including fixed energy, coincident emission, and position and momentum correlations [6]. Quantum ghost imaging is one such technique that uses spatial and temporal correlations between paired photons to form an image. With this method, one photon interacts with an object but retains no spatial information, while its entangled partner contains spatial information yet does not interact with the object [7]. By correlating these events, images can be constructed using only relevant photon pairs, reducing unwanted noise and improving image contrast [8]. Although quantum imaging has been extensively studied at optical and infrared wavelengths, its application in the x-ray and gamma-ray regime remains relatively unexplored [9]. Whereas optical spontaneous parametric down-conversion sources are ideal for low-energy quantum imaging in transparent media, positronium annihilation provides entangled pairs in the gamma regime, allowing for the extension of quantum imaging methods to high- Z and dense materials.

In this work, we present an experimental realization of quantum ghost imaging using entangled 511-keV gamma rays

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from positronium decay. By utilizing the spatial and temporal correlations inherent in these photon pairs, we demonstrate noninvasive imaging of high-density materials with significantly improved fidelity over classical approaches. Unlike classically correlated sources, e.g., thermal or shot-noise-limited emission, positronium decay always produces photons in pairs, arriving at the detectors with well-defined positions and times of arrival. We quantitatively compare classical and quantum imaging modalities across a range of object thicknesses and materials, using transmission and Michelson contrast metrics as benchmarks. Our results show that quantum-filtered images more accurately recover expected physical properties and suppress background noise. This work establishes the feasibility and advantages of gamma-ray quantum imaging, laying the foundation for future applications in security screening, industrial inspection, and other noise-limited radiographic environments.

II. METHODS

A. Detector specifications

Our imaging system consists of two Hamamatsu time-of-flight (TOF)-PET modules (C13500-4075YC-12) each consisting of a 12×12 array of 4×4 -mm photon-counting pixel arrays. Each pixel is coupled to a $4.14 \times 4.14 \times 20$ -mm lutetium-yttrium oxyorthosilicate scintillator. The total detection area of each module is approximately 50×50 -mm². These detectors are specifically designed for PET imaging and are therefore highly sensitive to photon energies above 100 keV [10]. The modules are equipped with two signal processing boards for multipixel photon counter data acquisition. Each board is composed of four application-specific integrated circuits which process the outputs of the 144 (12×12) pixels on the detector face [11].

The system outputs photon event data including spatial coordinates, timestamps, and time-over-threshold (ToT) values. The fine step timing resolution of the system is 15.1 ps, while the ToT timing resolution is 4 ns. The coincidence resolution time is less than 210 ps, with pixel-to-pixel timing variations within ± 15 ps. The modules are supported by a peripheral circuit that includes a +24-V power supply, a clock distribution unit for synchronizing events across modules, and relay and interface boards that transmit events to a computer for processing. The entire system is enclosed within a dark box during data collection and has an operating temperature range of 15 to 35 °C [11] (Fig. 1).

B. Experimental configuration

In this experiment, a Na-22 source (< 30 uCi) was used as a positron emitter, producing pairs of 511-keV photons through direct positron-electron annihilation and positronium decay. The TOF-PET modules were aligned along a common axis (Z) with their active areas facing each other and spaced 16 cm apart. The Na-22 source was positioned at the midpoint of this axis, equidistant from both detectors at 8 cm, and centered in the plane parallel to the detector faces (XY). Objects are placed in front of module B, which corresponds to the signal detector, but not in front of module A, corresponding to the idler detector. The objects used in this experiment were composed

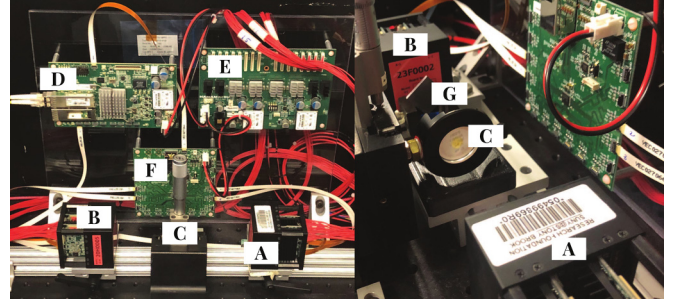


FIG. 1. A: TOF-PET module A, idler detector. B: TOF-PET module B, signal detector. C: Na-22 (< 30 uCi) source. D: Relay board. E: +24 V Power supply board. F: Clock distribution unit. G: Tantalum square object to be imaged.

of tantalum squares of the same thickness and steel washers, and a tungsten block (Fig. 2). Data were collected for 30 min at room temperature.

During operation, the system sees a gradual increase in the ToT value associated with a given photon event, likely due to thermal effects within the detector electronics. This drift is consistently observed across multiple pixels and is best modeled by logarithmic or power series fit curves for both modules (Fig. 3). To compensate for this, experimental data are taken only after 30 min has elapsed.

C. Data analysis

All data output from the detector are recorded in binary format and converted into Pandas dataframes using PYTHON scripts. Histograms of event timestamps and spatial coordinates are plotted to confirm the duration of each scan and to ensure that all detector pixels are functioning properly. The raw counts include a high level of electronic noise and unrelated background events, which must be filtered out to isolate photons originating from the Na-22 source [Fig. 4(a)].

1. Energy filtering: Preliminary analysis

Annihilation photons produced by positron-electron annihilation have a characteristic energy of 511 keV. By selecting for events the ToT values of which correspond to this energy, we can differentiate true annihilation photons from electronic noise and other nonsource counts. To identify appropriate ToT

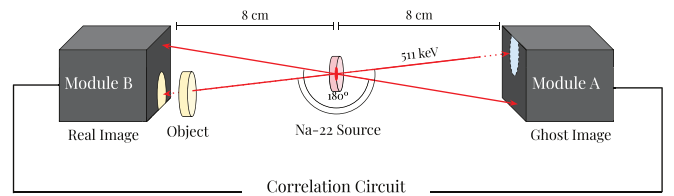


FIG. 2. Sketch of the gamma-ray imaging setup where a Na-22 source (< 30 uCi) emits 511-keV photon pairs 180° apart toward opposing detectors A and B (8-cm distance from each). An object before module B absorbs one photon; its partner is detected by module A. Correlation detection registers only unabsorbed pairs, enabling ghost imaging on module A.

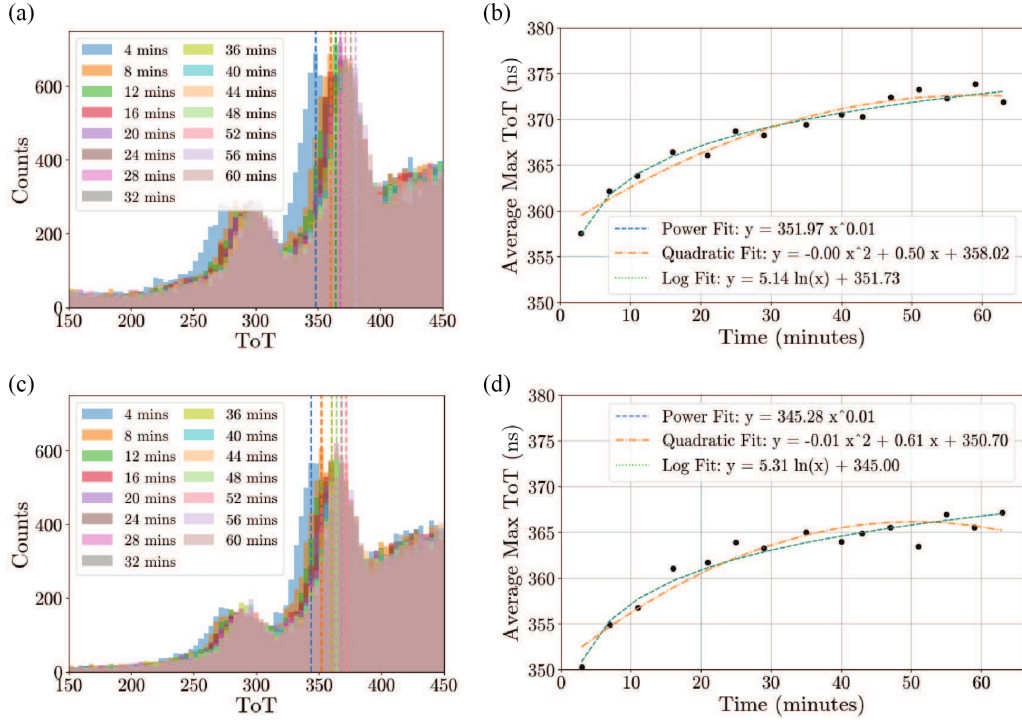


FIG. 3. Figures showing 15 3-min background-only scans which were collected at room temperature with 1-min pauses between them showing ToT-value drift during the first 60 min of system operation. (a)–(c) ToT histograms at each time point from (a) a pixel on module A and (c) a pixel on module B. (b)–(d) Mean ToT peak value (averaged across all pixels) over time, where the ToT peak is defined as the bin with the highest counts, for (b) module A and (d) module B. Logarithmic, power series, and quadratic fits were performed showing a saturation of the average mean ToT after approximately 30 min in both cases.

ranges, we compare the ToT histograms of the scan with the Na-22 source to those from a scan taken under identical conditions without the source present. Because the ToT values corresponding to 511-keV photons vary across modules and between individual pixels, this comparison is performed on

a pixel-by-pixel basis. For each pixel, we identify at least three consecutive ToT bins in which the event counts from the source scan exceed that of the background scan by a set threshold. This range is then used to isolate likely 511-keV events for each pixel [Fig. 4(b)].

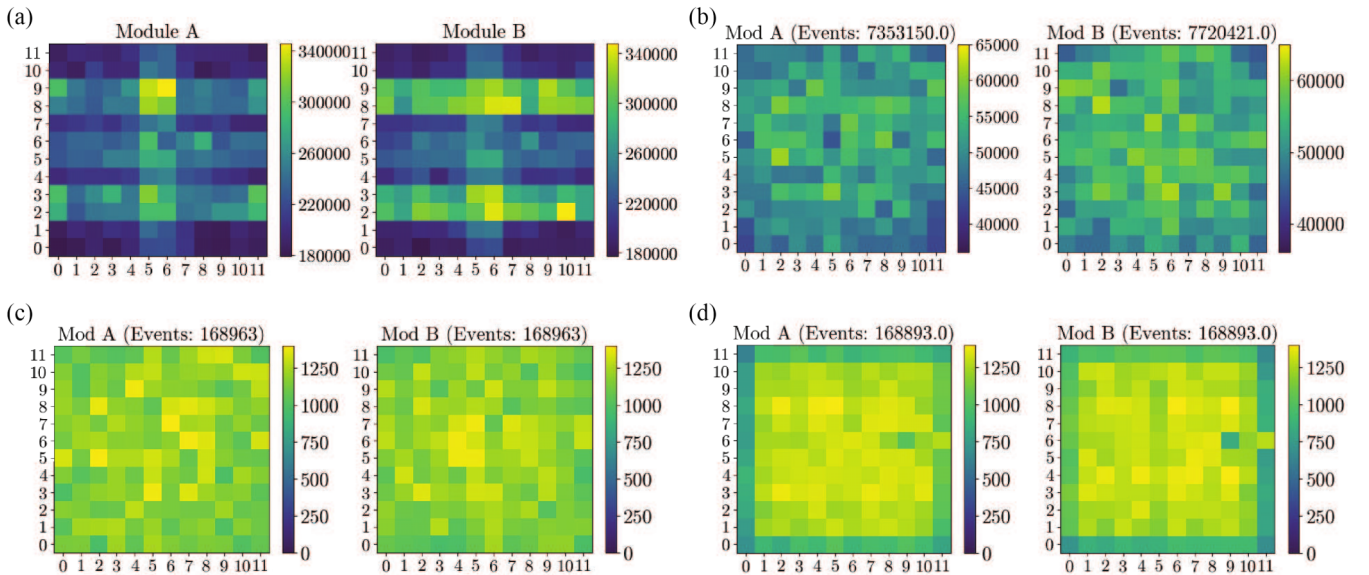


FIG. 4. Filtering procedure performed on a no-object source scan. (a) 2D histogram of raw event counts for module A and module B before filtering. (b) 2D histogram of energy-filtered event counts for module A and module B. (c) 2D histogram of energy-filtered and background-subtracted event counts for module A and module B. (d) 2D histogram of energy-filtered and coincidence pair event counts for module A and module B.

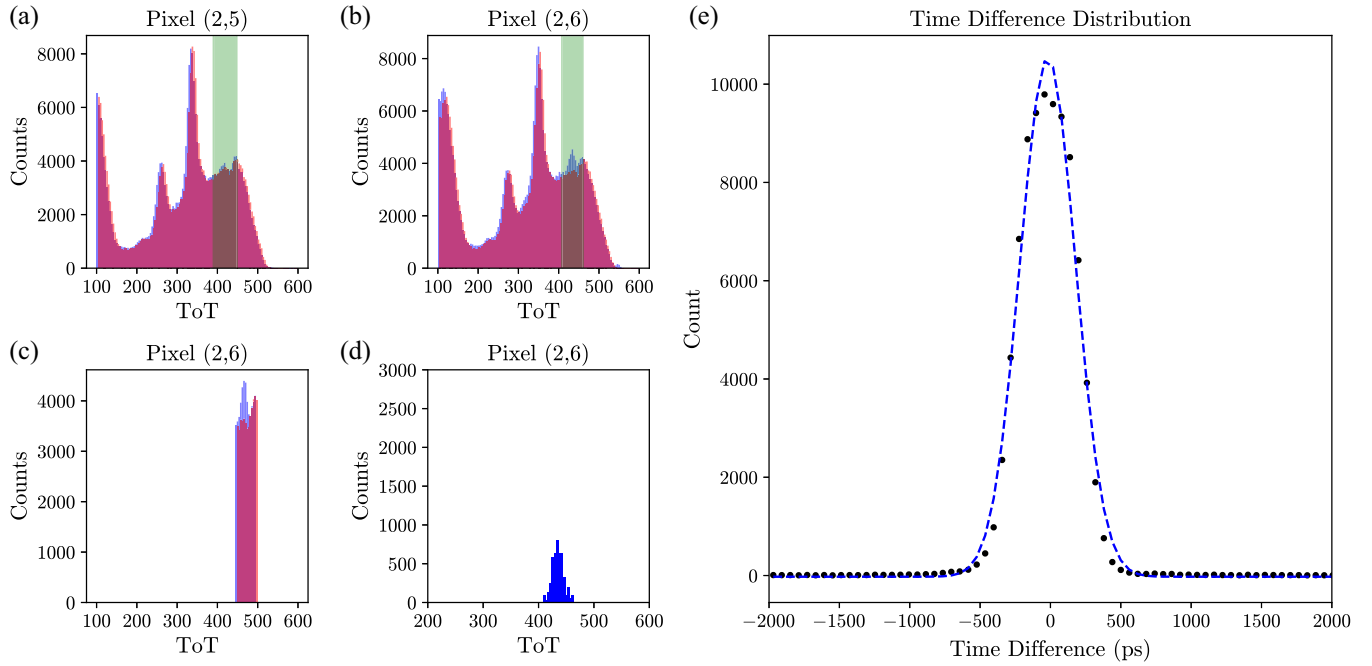


FIG. 5. ToT selection ranges for distinct and nondistinct source peaks. (a) ToT histograms of pixels covered by a low transmission object. There is no clear source peak where source counts (blue) are significantly above background (red). ToT range (green) is widened to ensure 511-keV events are captured regardless of peak location. (b) ToT histograms of pixels not covered by a low transmission object. There is a clear source peak where source counts are significantly above background. ToT range is narrow and specific. (c) Source and background ToT histograms for a high-transmission pixel. (d) Resulting background-subtracted source spectrum for the same pixel. (e) Time coincidence signal after ToT filtering. There is a Gaussian fit with $\sigma = 197.6$ ps.

This approach works well for high-transmission objects, where a clear source peak can typically be identified, even in pixels covered by the object. For low transmission objects, the source peak in pixels within the object region often is not prominent enough above the background to be easily distinguished. In cases where a narrow, specific ToT range cannot be defined based on a clear peak, a wider backup range is adopted to ensure all possible source counts are captured [Figs. 5(a) and 5(b)]. This prevents the accidental discarding of real 511-keV events. Once the range is set for each pixel, we filter the data to include only those events the ToT values of which fall within their pixel's accepted range.

2. Classical filtering: Background subtraction

Following energy-based selections, we can apply a classical filtering method that relies solely on measured counts, without any information guaranteed by quantum entanglement [Fig. 4(c)]. For each bin in the histogram of the energy-filtered ToT ranges, the number of recorded counts is subtracted from the number of counts in the corresponding bin of the source scan [Figs. 5(c) and 5(d)]. This process removes count associated with the background, resulting in an improved SNR of the source-based events and thus improved accuracy of downstream quantitative analysis.

3. Quantum filtering: Coincidence pairing

An alternative method for refining the energy-filtered dataset is quantum correlation counting [Fig. 4(d)]. Gammas emitted by electron-positron annihilation are inherently

quantum entangled and emitted simultaneously in opposite directions from a common origin. Given that the gamma emission source is theoretically centered between the two detectors, these photons are therefore expected to arrive at opposing modules at the same time. By selecting pairs of events, where each pair consists of gamma signals from each module occurring within 500 ps of each other, we can effectively suppress uncorrelated background counts and isolate true positronium decay photon pairs. The ± 500 -ps coincidence window (approximately $\pm 2.5\sigma$) was chosen to balance detection efficiency with accidental-pair suppression; increasing this window may slightly improve the number of pairs detected at the expense of lower SNR [Fig. 5(e)].

Slight temporal delays in the reset signal, which reinitializes timestamps to zero at the beginning of each scan, can create an offset in the timing of events across different signal processing boards in the two detectors. This time difference leads to false coincidences and the loss of some true coincident photon counts during pair formation. To address these possible offsets, the Gaussian distributions of the coincidence time spectra between different boards in the two detectors were aligned such that their peaks were centered at the origin prior to pair formation.

This filtering process results in a ghost image on module A generated by the absence of coincident pairs. This absence occurs because photons absorbed by the object do not reach the signal detector; therefore, even if the reference photon is registered by the idler detector, a coincidence will not be identified. The ghost image will appear upside down and flipped because the positions of the entangled gammas are

anticorrelated due to the conservation of momentum (plucket). In other words, if one photon is detected at a certain position, its entangled partner will be at the diametrically opposite position.

4. Transmission and Michelson contrast calculations

The quality of the ghost images from both the classical and quantum methods described above is evaluated using quantitative metrics. One key metric is the transmission of 511-keV annihilation gamma rays through the objects. This is compared to the expected transmission predicted based on the objects' thickness and material properties. Assessing how closely the experimental transmission aligns with the theoretical expectation provides a measure of the effectiveness of the filtering method and overall image fidelity. We can calculate the theoretical transmission (T_t) for a known object thickness using Eq. (1), where u is the mass attenuation coefficient, p is the density, and x is the thickness:

$$T_t = 100e^{-upx}. \quad (1)$$

Experimental transmissions (T_e) are calculated from the filtered data sets using Eq. (2), where O_{avg} is the average count per pixel in a defined object region and S_{avg} is the average count per pixel in a defined nonobject region. The closer the experimental transmission is to the expected value, the better the filtering method and overall image quality:

$$T_e = 100 \frac{O_{\text{avg}}}{S_{\text{avg}}}. \quad (2)$$

Another quantitative measure of image quality is the Michelson contrast (V), which calculates the relative difference in intensity between object and nonobject regions. It is defined in Eq. (3). Michelson contrast values range from 0 to 1, where values closer to 1 indicate a better image contrast:

$$V = \frac{S_{\text{avg}} - O_{\text{avg}}}{S_{\text{avg}} + O_{\text{avg}}}. \quad (3)$$

By calculating these metrics processed with either classical or quantum filtering, we can compare their performance in terms of image fidelity and contrast.

III. RESULTS

To assess the level of noise remaining after classical and quantum-based filtering, we imaged a solid tungsten block ($x = 17.3$ mm, $p = 19.3$ g/cm³, $u = 0.1338$ cm²/g). Given tungsten's high density and mass attenuation coefficient, this object absorbs 98.8% of incident gamma rays, corresponding to a theoretical transmission of 1.2% in the object region [12]. Under these conditions, nearly all detected events within the object region should be nonsource photon events, making this scan an effective test case for evaluating the noise suppression capabilities of each filtering method.

In Figs. 6(a)–6(d), the object region in the image processed using the classical filtering method contains a higher number of events and more pronounced pixel-to-pixel count fluctuations than the quantum filtering method. Pixel intensities in the object region of the classically filtered images correspond to an average transmission of $37 \pm 7.2\%$. The

quantum-filtered image shows object region pixel intensities with a calculated transmission of $4.5 \pm 0.4\%$, which is significantly closer to our expected transmission value. This reduction in noise in the quantum-filtered image indicates that it more effectively removes background events and better preserves the expected transmission of the object.

Furthermore, we conducted analysis on the positional correlations between coincident events within and outside the object region of the quantum-filtered dataset [Figs. 6(e) and 6(f)]. We investigated the spatial distribution of coincidence pairs by selecting events originating from a fixed pixel in the nonobject region, e.g., pixel (8, 7) on module B, and identifying which pixels on module A registered the corresponding paired events. We repeated this analysis for a pixel located within the object region, e.g., pixel (4, 5) on module B, to compare. For the pixel in the unattenuated region of module B, the majority of coincidence counts on module A occurred at the positionally correlated pixel. The adjacent pixels registered a smaller number of counts, while pixels farther from the correlated position recorded few to no events. This is consistent with the majority of detected events being true coincidence pairs. In the object region, we observed that while the positionally correlated pixel on module A still registered the highest number of coincidence counts, a greater proportion of events were distributed across distant, noncorrelated pixels as compared to the nonobject region. This suggests that while some coincidence counts within the object region represent true pairs, a higher proportion of events in the object region do not represent true coincidence pairs.

To evaluate the effectiveness of classical and quantum filtering methods across objects with varying levels of attenuation, we collected 30-min room-temperature scans of tantalum samples (2×2 cm², $p = 16.65$ g/cm³, $u = 0.1314$ cm²/g) at five different thicknesses ($x = 2.56, 5.12, 7.68, 10.24$, and 12.80 mm) [12]. Each scan was processed using both filtering methods (Fig. 7). For more meaningful comparisons, the classically filtered datasets were proportionally truncated to match the total number of counts in the corresponding quantum-filtered datasets. In the classically filtered images, both modules A and B contain real images, and therefore, only module B has object information. In contrast, the quantum filtering method produces a real image on module B and a corresponding quantum ghost image on module A, both of which contain object information. The quantum-filtered images exhibit visibly reduced pixel-to-pixel noise and a more uniform signal across the image plane, while the classically filtered images show more visible fluctuations, particularly in low-count regions.

Using these five scans, we calculated both transmission and Michelson contrast values. For a tantalum object one to five squares thick, the expected transmissions [using Eq. (1)] are 57.1, 32.6, 18.6, 10.6, and 6.1%, respectively. Corresponding transmission values calculated from the classically filtered images [using Eq. (2)] are 75.8 ± 7.6 , 38.9 ± 7.9 , 44.6 ± 8.9 , 33.7 ± 8.9 , and 34.0 ± 6.8 , while those from the quantum-filtered images are 64.1 ± 3.3 , 37.8 ± 2.6 , 26.3 ± 2.8 , 16.1 ± 1.0 , and 9.4 ± 1.2 , where errors are determined using the standard deviation of pixel count distributions within both object and nonobject regions. The quantum-filtered transmission values are overall more accurate, aligning more closely with

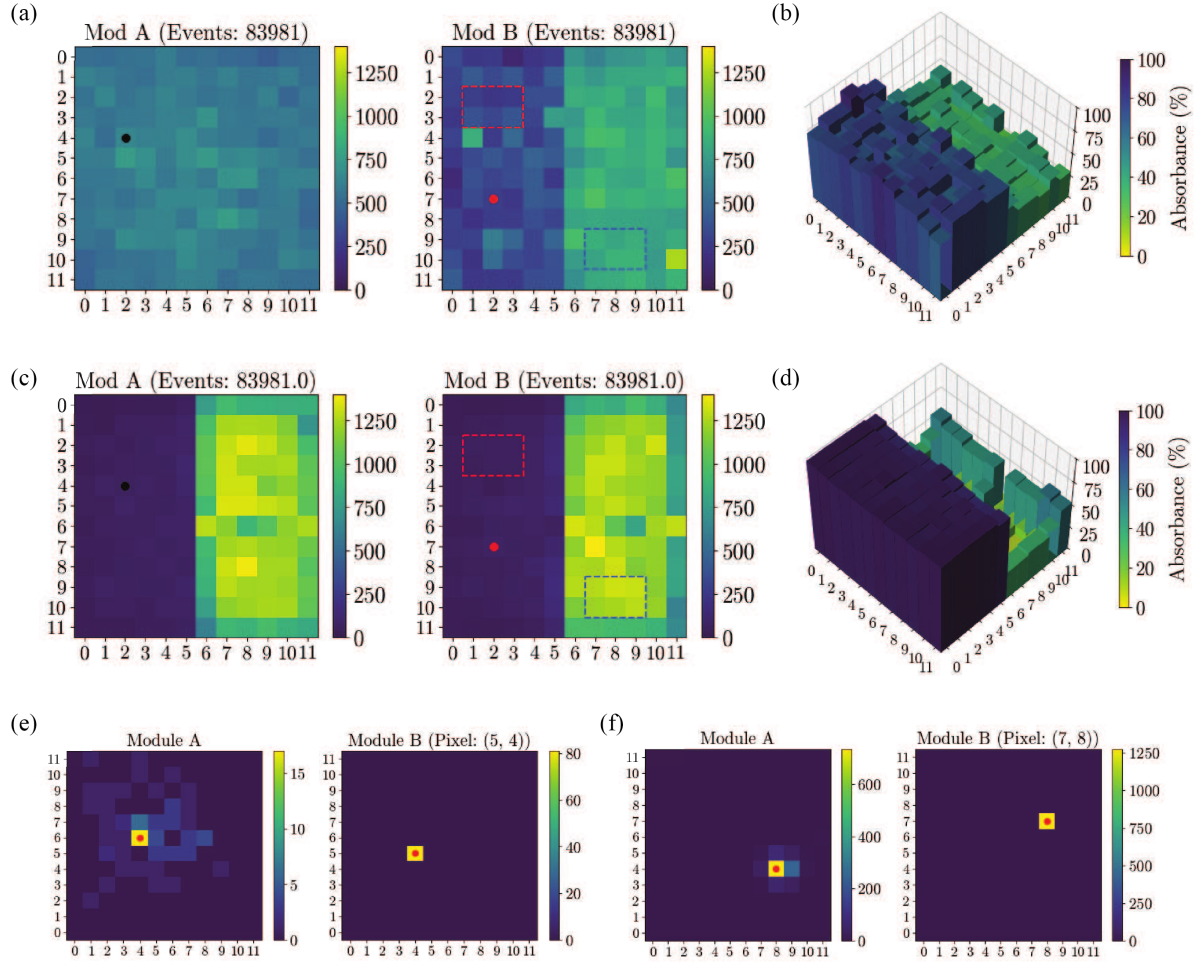


FIG. 6. Classical and quantum filtering methods applied to a 0–100% transmission scan. The left half of module B contains a tungsten block of 17.3-mm thickness. (a) Energy-filtered and background-subtracted 2D histogram of detector modules A and B. (b) 3D histogram of background-subtracted pixel counts across module B. (c) Energy-filtered and coincidence-paired 2D histogram. (d) 3D histogram of coincidence-paired pixel counts across module B. (e) Coincident events on module A corresponding to pixel (4, 5) on module B, located within the object region. Red dots mark the correlated module A and B pixels. (f) Coincident events on module A corresponding to pixel (8, 7) on module B, located outside the object region. Red symbols mark object regions. Blue symbols mark nonobject regions in the real image module. Red dots are positionally correlated.

the expected values across all tantalum thicknesses except 5.12 mm, where the performance was not significantly different [Fig. 7(a)]. Additionally, relative uncertainties associated with the classical contrast measurements were consistently larger, indicating greater pixel-level variance in event counts across object and nonobject regions as compared to the quantum method.

Similarly, the calculated Michelson contrast values were nominally higher for quantum-filtered scans, with values of 0.22 ± 0.03 , 0.45 ± 0.05 , 0.59 ± 0.06 , 0.72 ± 0.05 , and 0.83 ± 0.05 for one to five squares, respectively. The classically filtered scans, by comparison, produced lower contrast values of 0.14 ± 0.05 , 0.44 ± 0.08 , 0.38 ± 0.08 , 0.50 ± 0.10 , and 0.49 ± 0.08 . This quantitative metric performs better in quantum scans than classical scans for all thicknesses except 5.12 mm, showing that quantum entanglement imaging produces a better signal-to-noise ratio [Fig. 9(b)]. Like the transmission metrics, the smaller uncertainties in contrast values associated with quantum images as compared to classical

suggest a more uniform distribution of events across the detector, which improves both image quality and accuracy.

To investigate the performance of our system with lower-attenuation materials with a discernibly different geometry from the tantalum squares, a stack of steel washers (1-in. outer diameter $\times$ $\frac{1}{4}$ -in. inner diameter $\times$ 4.6 mm) was scanned. Steel is mainly composed of iron, so the density and relevant mass attenuation coefficient can be approximated as $\rho = 7.874 \text{ g/cm}^3$ and $\mu = 0.0833 \text{ cm}^2/\text{g}$, respectively [12]. Based on these parameters, the expected transmission through the washer stack is approximately 74%. The object's circular shape with a central hole is visually resolved in both quantum and classical scans (Fig. 8). The measured transmission values are 76.0 ± 2.9 in the quantum scan and 81.5 ± 8.1 in the classical scan. The corresponding Michelson contrast values between the object and nonobject regions are 0.14 ± 0.02 (quantum) and 0.10 ± 0.05 (classical).

We then analyzed the evolution in transmission and Michelson contrast metrics as a function of tantalum thickness

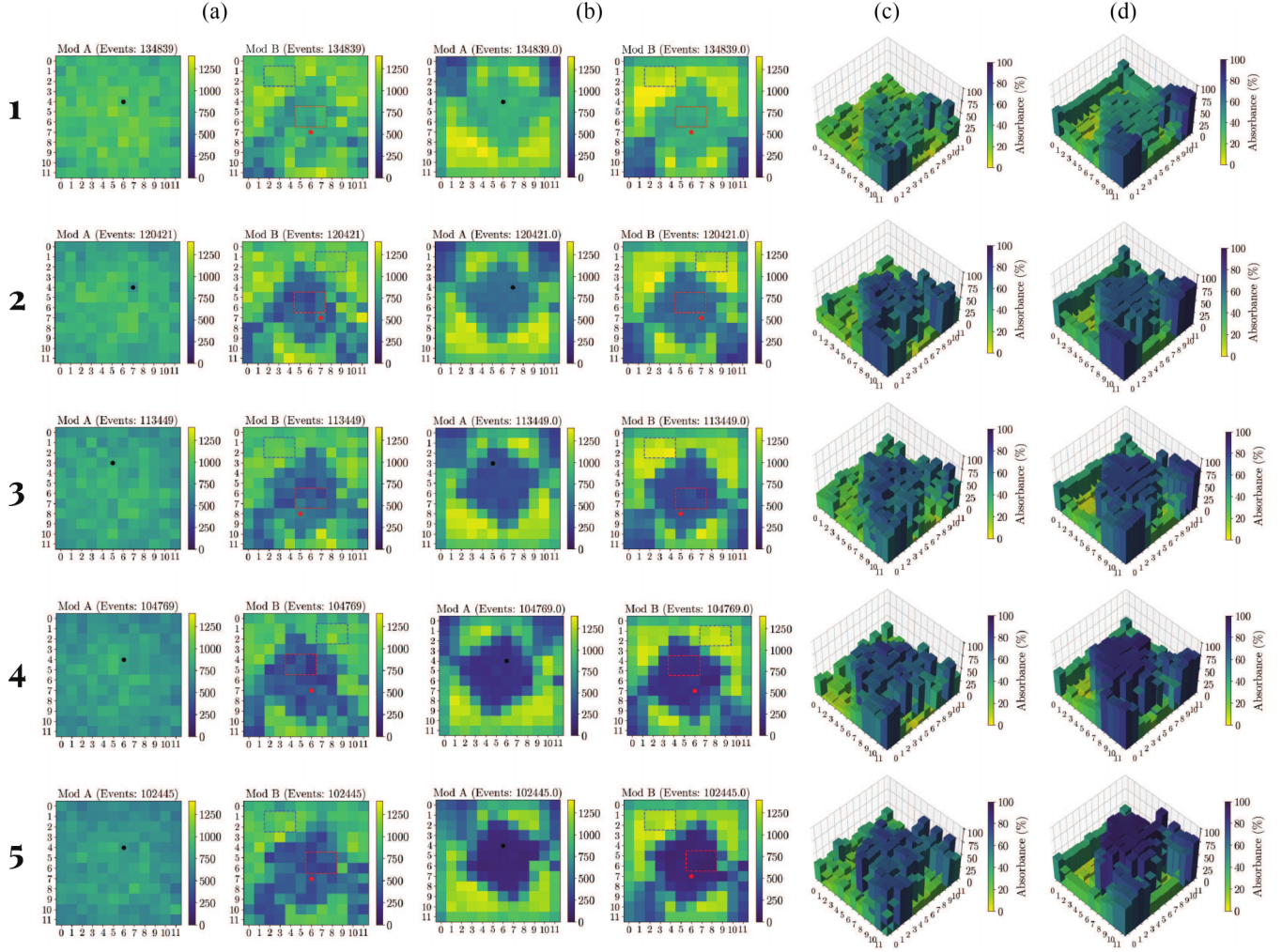


FIG. 7. Classical and quantum filtering methods applied to tantalum objects of increasing thicknesses. All scans were collected for 30 min at room temperature. Tantalum thicknesses are (1) 2.56 mm, (2) 5.12 mm, (3) 7.68 mm, (4) 10.24 mm, and (5) 12.80 mm. The objects are clamped diagonally, with the largest face parallel to the detector plane. (a) Classically filtered images using energy selection and background subtraction. Rightmost images contain the object. (b) Quantum-filtered images using energy selection and coincidence pairing. Rightmost images show the real image, and leftmost images show the positionally correlated ghost image. Red symbols mark object regions. Blue symbols mark nonobject regions in the real image module. Red dots are positionally correlated with corresponding black dots. (c) 3D histograms of classically filtered images from module B, the real image module. (d) 3D histograms of quantum filtered images from module B, the real image module.

to best evaluate the performance of classical and quantum imaging techniques for a variety of object densities (Fig. 9). Using Eq. (2), we converted the physical thicknesses of the tungsten- and steel-based objects to tantalum-equivalent thicknesses of 20.4 and 1.38 mm, respectively. The trend observed in the quantum-filtered data reflects the expected nonlinear decrease in transmission with increasing thickness. Classically filtered values deviate significantly from this trend at higher object densities, where gamma-ray transmission is low. This implies that quantum-filtered images more accurately preserve the true structure of the object, as reflected by their transmission values aligning with theoretical expectations. Furthermore, while the Michelson contrast exhibits only marginal improvement for low-density objects under quantum filtering, it nearly doubles for high-density objects, marking a significant advantage to utilizing quantum methods.

IV. DISCUSSION

The improvement in image quality for low-transmission objects specifically aligns with findings from other studies that have shown quantum imaging techniques to offer the greatest advantage with low photon counts [13]. For instance, Morris *et al.* were able to generate high-quality images using correlated photon pairs even when the average photon rate was less than one per pixel, a limitation that would severely impact classical imaging methods [14]. In our experiment, thick tantalum objects (> 5.12 mm) transmit a very small number of annihilation photons compared to background counts, making it difficult to distinguish true 511-keV photons from the large amounts of noise in each pixel without the use of quantum correlations. This is consistent with results from a 2024 study that simulated quantum ghost imaging with noisy detectors. Here, researchers demonstrated that for low photon

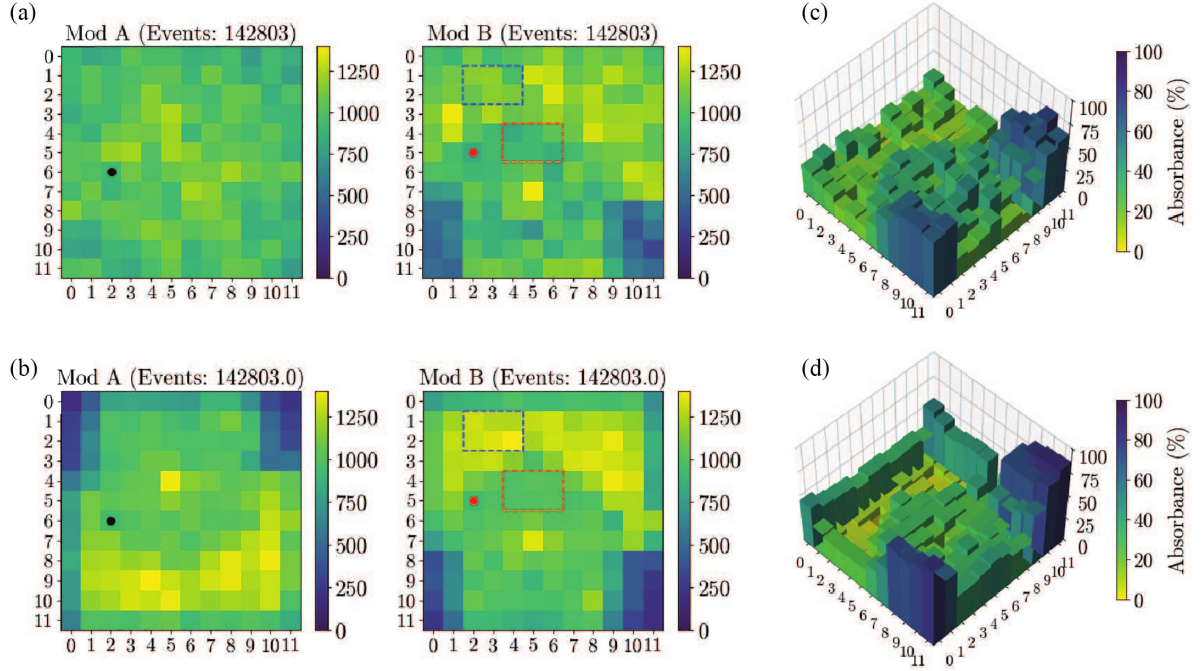


FIG. 8. Classical and quantum filtering methods applied to stainless steel washers. All scans are collected for 30 min at room temperature. The objects consist of four stacked washers, 1-in. outer diameter, 1/4-in. inner diameter, 1.15-mm thickness each. The objects were clamped with the largest face parallel to the detector plane. (a) Classically filtered images using energy selection and background subtraction. Rightmost images contain the object. (b) Quantum-filtered images using energy selection and coincidence pairing. Rightmost images show the real image, and leftmost images show the positionally correlated ghost image. (c) All scans collected for 1800 s at room temperature. (d) 3D histograms of quantum filtered images from module B, the real image module. Red symbols mark object regions. Blue symbols mark nonobject regions in the real image module. Red dots are positionally correlated with corresponding black dots.

counts and non-negligible dark count rates, quantum imaging approaches could generate signal-to-noise ratios up to an order of magnitude greater than classical [15]. The object region of our high-density scans meets the conditions of low photon

count and high background count, and as such, our quantum imaging techniques result in better contrast and transmission metrics than classical techniques, which struggle to isolate true annihilation gamma-ray photons from background.

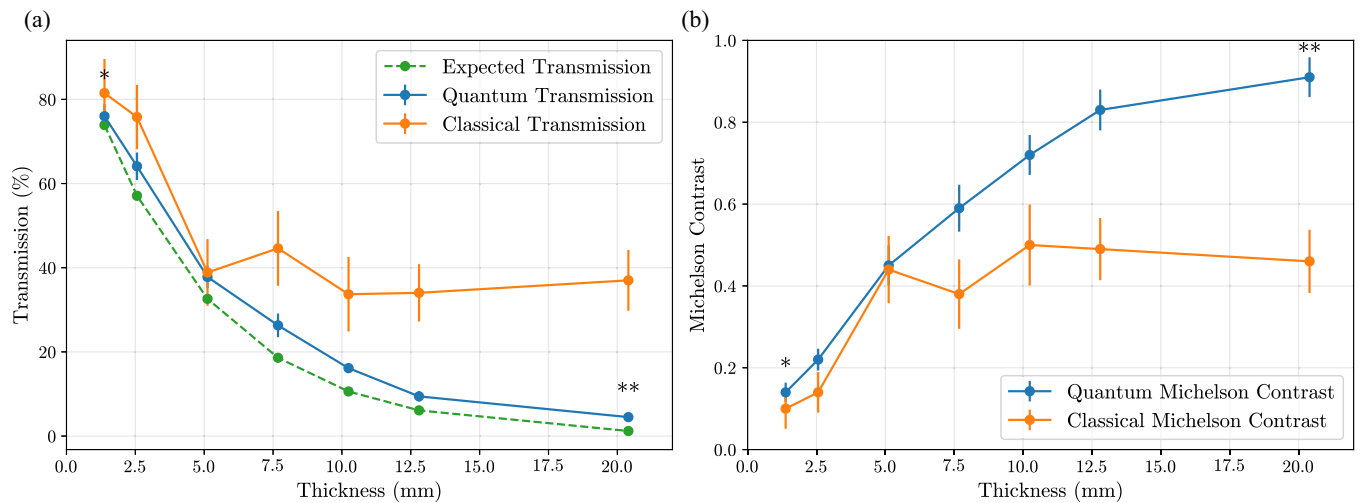


FIG. 9. Transmission and Michelson contrast as a function of tantalum thickness. (a) Transmission values from quantum-filtered (blue) and classically filtered (orange) images, compared to expected values (green) at each thickness. (b) Michelson contrast values from quantum-filtered (blue) and classically filtered (orange) images across the same range of thicknesses. Transmission and Michelson contrast values are calculated via Eqs. (2) and (3). Error bars indicate the standard deviation of photon count per pixel propagated through Eqs. (2) and (3). Tantalum thicknesses are 2.56, 5.12, 7.68, 10.24, and 12.80 mm. A tantalum thickness of 1.38 mm corresponds to 4.6 mm of stainless steel washers. A tantalum thickness of 20.4 corresponds to 17.3 mm of tungsten.

Our findings are also consistent with works that examine the applications of quantum-enhanced imaging with high-energy gamma-ray photons specifically. Researchers have shown that the polarization entanglement of ghost imaging photon pairs persists at 511 keV, and this entangled nature can be utilized to improve SNR in environments dominated by noisy or scattered radiation via coincidence-count filtering [3]. While these techniques have already demonstrated improved image resolution and reduced background in PET scans [16], our results point toward expanding the applicability beyond PET scans. Recent theoretical work has outlined the feasibility of quantum ghost imaging with gamma photons, stating that entangled gamma pairs could be used to generate ghost images where direct detection is limited by low photon counts or noise [9]. Our study provides experimental support for these possibilities by showing that quantum imaging methods can recover more accurate transmission values and sharper image contrast under such conditions.

Our implementation uses a low-activity source optimized for correlation fidelity, demonstrating the feasibility of quantum-enhanced gamma imaging. Future higher-flux systems could extend this approach to large-scale or rapid imaging applications, such as cargo scanning. In cargo scanning, analysis of dense materials with minimal noise input is essential for accurate detection of threats and reconstruction of images [17], but the high scattering environment of cargo containers undergoing gamma-ray radiography interferes with this objective [18]. A prior study on quantum decoherence demonstrated that annihilation photon pairs can maintain polarization entanglement even after undergoing moderate material interactions, including Compton scattering [6]. This implies that the benefits of quantum-based imaging uncovered in this study are applicable to this environment, and a coincidence-based filtering method has the potential to reduce the impact of any overwhelming noise and scattering present during a container scan.

V. CONCLUSION

This work has culminated in experimentally realized quantum ghost images using positronium decay annihilation photons. In the imaging of high-density objects with a highly noisy detector, quantum imaging methods outperform classical imaging methods in both contrast and transmission accuracy metrics. These findings provide experimental validation of theoretical predictions regarding the viability of quantum imaging at high photon energies as well as initial evidence of a quantum advantage in gamma-ray imaging. Furthermore, our work has practical applications in fields such as homeland security and noninvasive inspection, including improved cargo and shipping container screening performance in noisy imaging conditions. Future work should explore the performance of both filtering methods in the imaging of very high transmission objects (>90% expected transmission), where small contrast differences are easily masked by noise.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [19].

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