様　式　C－19、F－19－1、Z－19　（共通）

KAKENHI 科研費

科学研究費助成事業　　研究成果報告書

令和　３ 年　 ６ 月 １７ 日現在

機関番号：１２６０１
研究種目：研究活動スタート支援
研究期間：2019～2020
課題番号：１９Ｋ２３４３６

研究課題名（和文）Novel imaging technique using Compton cameras and polarized-entangled gamma photons

研究課題名（英文）Novel imaging technique using Compton cameras and polarized-entangled gamma photons

研究代表者
Ｃａｒａｄｏｎｎａ　Ｐｉｅｔｒｏ（Caradonna, Pietro）

東京大学・カブリ数物連携宇宙研究機構・特任研究員

研究者番号：１０８４６５２０

交付決定額（研究期間全体）：（直接経費）　　1,900,000円

研究成果の概要（和文）：陽電子放出断層撮影（PET）において、コンプトン散乱されたガンマ線を効率よく使うことでPETの感度を向上させることができる。我々は電子陽電子消滅によって生ずる量子もつれ下の光子対の散乱の再定式化をストークス行列を用いて行った。そして量子もつれのみに起因する散乱断面積の構造を発見した。また、コンプトンカメラで電子陽電子消滅線の散乱ガンマ線を検出する場合に「タッチコーンパターン」と呼ぶ特定の事象を用いて散乱位置を特定することができることを示した。コンプトンカメラを用いて、ガンマ線の体内での散乱箇所を精度よく見出すことができれば、被曝をさげつつ感度の高いイメージングを行う診断装置の開発につながる。

研究成果の学術的意義や社会的意義
The scientific of the success of this research would pave the way for the development of a single modality machine which combines the analytical reach of a combined PET and CT scanner into one system resulting in reduced radiation exposure to the patient, as well as correcting for attenuation.

研究成果の概要（英文）：We apply quantum entanglement to correct for scattering loses in Positron Emission Tomography (PET). We have reformulated Compton scattering of entangled photons in terms Stoke’s matrices, making it easier to understand the underlying scattering dynamics, and we found structures in the cross-section which are solely due to entanglement.
We found a particular Compton scattering configuration to find the scattering sites, which we call “the touch cone configuration”. This idea is under a provisional patent and will be applied in future work. We have also included atomic electron binding effects as well, which will make future GEANT4 simulations reflect more accurately the scattering processes in biological material.
The significance of locating scattering sites paves the way for the development of a single modality machine which combines the analytical reach of a PET and CT scanner resulting in reduced radiation exposure to the patient, as well as correcting for attenuation.

研究分野：Quantum entanglement and its medical imaging

キーワード：Entanglement　Compton scattering　medical imaging　Compton Cameras

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

The holy grail of Positron Emission Tomography (PET) is to have a level of sensitivity great enough to detect the onset of metastatic cancer using only the signal of back-to-back 511 keV gammas from positron annihilation.

The obstacle that prevents modern day scintillation-PET machines from reaching the required sensitivity levels is the incapability of these machines to pair-up photons when one or both have Compton scattered. Between 10% and 70% of the time one of the photons will Compton scatter before exiting the tissue under study. Furthermore, the unscattered photons that reach the scanner’s detector provide no information of the attenuating medium, even though Compton scattering of back-to-back gamma photons encodes valuable anatomical information. Unfortunately, this information remains inaccessible to scintillation-based PET scanners.

Furthermore, an attenuation map is required to correct for uneven losses of signal. Conventionally, this map is obtained using X-ray computed tomography, which means that the patient is exposed to further ionizing radiation. The envisioned technology would both better exploit the administered positron emitter dose and eliminate the need for additional X-ray exposure.

The accuracy of measuring the position of these scattering sites is independent of the positron range; it is only limited by technology. Not only can this idea provide structural information, but the location of these scattering sites can also be used to correct for photon attenuation which leads to an increased sensitivity of metabolic activity. An increase in PET sensitivity of metabolic activity can lead to reduced radioactive exposure to the patient plus providing valuable three-dimensional anatomical information for the medical practitioners.

２．研究の目的

The purpose of this research is to show that a pair of Compton cameras can recover the back-to-back signal required to detect the presence of metastatic cancer and extract anatomical information by plotting the scattering sites in the case when one of the pair of photons Compton scatters inside the patient while the other passes straight through.

３．研究の方法

This theoretical investigation has found that Compton cameras can increase the detection sensitivity by correcting the trajectory of a scattered photon, in the case when one of the back-to-back photons has Compton scattered inside the patient. This will be achieved using Compton cameras, which are advanced imaging devices that employ position-sensitive photon scattering plates and absorption plates to reduce the uncertainty of the trajectory of the incident photon to the surface of a so called “Compton cone”. By fixing the scattering plane with the help of the unscattered 511 keV photon, the full geometry of the positron annihilation event in-tissue can then be recovered, and therefore increasing the detection sensitivity. Further still, this investigation shows that, in principle, the scattering site can still be found even when one of the photons Compton scatters inside the patient. Plotting all possible sites can provide a novel method of generating 3D anatomical maps.

Calculating gamma ray collision cross sections involves a deep understanding of quantum electrodynamics (QED). The originality of this research lies in providing a method for calculating cross sections that sidesteps the need to perform QED calculations. Also, since the calculation is essentially rooted in geometry, we have established an original visualization technique using a CAD program to illustrate and model the QED interaction. This helps guide the mathematical formulation and at the same time provides a visual aid to communicate the ideas to my peers and a broader interested audience.

These original methods have made it possible to study the various types of scattering patterns produced by the polarization dependant double and triple Compton scattering events. We have derived the necessary analytical solution of the triple Compton collision cross section for a pair of 511 keV polarization-entangled photons. Equation (1) models the case when one of the photons Compton scatters inside a patient and each photon is detected by a pair of Compton cameras used in coincidence mode.

$$d^3\sigma(\theta_1,\theta_2,\theta_3,\eta_1,\eta_3;E_o) = \frac{d\Omega_1 d\Omega_2 d\Omega_3}{16}\sum_{a=0}^{1}\langle I|\,T_{\gamma_1}(\theta_1;E_o)R_\gamma\left(\eta_1-\frac{a\pi}{2}\right)|{\rightarrow_-}\rangle\,\langle I|\,T_{\gamma_3}(\theta_2,\theta_3;E_o)R_\gamma(\eta_3)T_{\gamma_2}(\theta_2;E_o)R_\gamma\left(\frac{a\pi}{2}\right)|{\uparrow_+}\rangle \tag{1}$$

４．研究成果

This research askes the following scientific questions:

·Is it possible to locate the scattering sites in the case when one of the 511 keV photons Compton scatters inside a patient before reaching the Compton cameras?

·Using the location of the scattering sites, by what factor can the detection sensitivity be increased?

·Can we obtain 3D anatomical information by mapping the scattering sites as predicted by theory?

The purpose of answering these questions is primarily to increase the sensitivity for detecting the presence of metastatic cancer. Preliminary calculations based on a typical PET scan gives an estimate of around 107 scattering sites which can be used to reconstruct the back-to-back photons. This estimate is comparable to the number of unscattered (back-to-back) coincidence events (between 106 to 109), which implies that the detection efficiency may be at least doubled using this technique.

The domestic and overseas trends for imaging modalities are the development of multiple modality units such as PET-CT, and PET-MRI. This is because individual modalities are limited both in scope and in terms of the type of information can be extracted from a given signal. However, these multi-modality machines lead to higher manufacturing costs, and in the case of PET-CT, the patient is also subjected to doses of both X-ray and gamma-ray radiation. This research suggests that Compton-PET scanners can reduce the cost of these machines making them more safer and affordable to developing countries.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　2件／うちオープンアクセス　3件）

１．著者名	４．巻
Caradonna Peter	115011
２．論文標題	５．発行年
Amplification of polarization correlations in Compton scattering of hard x-ray Bell states	2020年
３．雑誌名	６．最初と最後の頁
Journal of Physics Communications	1-10
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1088/2399-6528/abcb45	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	該当する

１．著者名	４．巻
Caradonna Peter、Reutens David、Takahashi Tadayuki、Takeda Shin’ichiro、Vegh Viktor	3
２．論文標題	５．発行年
Probing entanglement in Compton interactions	2019年
３．雑誌名	６．最初と最後の頁
Journal of Physics Communications	105005～105005
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1088/2399-6528/ab45db	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	該当する

１．著者名	４．巻
P. Caradonna, S. Takeda	-
２．論文標題	５．発行年
Compton scattering of hard X-ray Bell state photons created by spontaneous parametric down-conversion	2020年
３．雑誌名	６．最初と最後の頁
Journal of Physics Communications	-
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
なし	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	－

〔学会発表〕　計0件

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関