Towards total-body modular PET for positronium and quantum entanglement imaging

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Abstract—**The purpose of the reported research is (i) the elaboration of the new imaging method based on the in-vivo measurement of properties of positronium produced inside patient during positron emission tomography, and determination of correlations between properties of positronium inside the cancer tissues and histopathological characteristics of cancers, as well as (ii) exploration of possibilities of the determination of the linear polarization of annihilation photons and development of novel prognostic indicators for cancer diagnostics based on the quantum information from (multipartite) entanglement of photons originating from the positronium decay.**

During PET diagnosis positronium may be trapped inside free volumes between and within molecules of the examined patient. Currently, in the PET technique, the phenomenon of positronium production is neither recorded nor used for imaging. Yet in about 40% cases, the electron-positron annihilation proceeds in the tissue via creation of positronium. The properties of positronium (such as e.g. mean lifetime or ratio of decay rates into two and three photons) depend on the size of the free volumes between atoms and there are indications that they are correlated with the stage of the development of metabolic disorders of the human tissues. Therefore, an image of properties of positronium formed inside the human body may deliver new information complementary to SUV index and useful for the diagnosis.

Moreover, recent theoretical studies have proven that the entanglement in the three-photon state from the decay of ortho-positronium survives surprisingly also for mixed scenarios expected in human tissues. Hence, detecting entanglement of photons originating from positronium may enable the extraction of quantum properties of the surrounding tissue environment.

We discuss (i) results of the feasibility studies of the positronium mean-lifetime image reconstruction with the total-body PET scanner from plastic scintillators, as well as (ii) results of pilot studies of the mean lifetime of positronium in the healthy and tumorous tissues operated from the patients. Performed experiments show that properties of positronium atoms in uterine tissues operated from human patients reveals meaningful differences between healthy and tumorous tissues. We also discuss results of the feasibility studies of the polarization of annihilation photons with the J-PET tomograph in which annihilation photons interact predominantly via Compton scattering. Registration of both primary and scattered photons enables to determinate the linear polarization of the primary photon on the event by event basis and hence enables to witness the entanglement of annihilation photons in polarization based on Mutually Unbiased Bases. The performed simulations indicate that in the future with the total-body PET and improved time resolution it shall be feasible to reconstruct images of positronium properties in-vivo during the routine PET diagnosis.

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Manuscript received December 15, 2018.

I. Introduction

The detection system of the conventional PET tomograph is programmed to record data on annihilation into two photons with energy of 511 keV, and it gives information on the distribution of a radiopharmaceutical in the body of the object. As we described in detail in [1], positron injected to the human body (during β^+ decay of the radio-tracer) can annihilate directly with one of electrons of the examined object or it can create the bound state of electron and positron called positronium atom (Ps). Positronium may be trapped inside free volumes between molecules of the examined patient. Currently, in the PET technique, the phenomenon of positronium production is neither recorded nor used for imaging. In this conference proceedings we repeat breafly the text from the references [1], [2]. In about 40% cases, the electron-positron annihilation proceeds in the tissue via creation of positronium [3], [4] and even in water the orthopositronium is formed with the probability of about 25% [5]. Orthopositronium decays in vacuum into three photons, however, in the human body, due to the large probability of the pick-off processes the three photons events (both from ortho-positronium decays and direct $e^+e^- \to 3\gamma$ processes) constitute altogether only about 0.5% of electron-positron annihilations and orthopositronium mean lifetime decreases from 142 ns in vacuum to about 2 ns in the tissue [4], [6]. However, such relatively low fraction of three-photon annihilations occurring in the human tissues may be compensated by increased sensitivity of the PET detector and by improved spatial resolution of the single-event annihilation point reconstruction [7], [8]. At present, PET tomographs record and use for image reconstruction less than 1% of anihilation events occuring in the body [9], [10], thus leaving room for significant improvement of three-photon statistics by the increase of sensitivity, without a need to extend the duration of examinations or to increase the dose of radiopharmaceuticals. In this context it is important to stress that there is an ongoing development of novel modalities for the whole and total-body PET imaging which shall be characterized by about 40 times higher sensitivity with respect to the presently available PET systems [9], [10]. Moreover, additional improvement in the time resolution to 100 ps combined with the total-body PET may effectively increase the sensitivity even by factor of 200 [9], [10]. Finally, it is worth noting that if the time resolution would be improved in the future down to 10 ps, as advocated by Lecoq [11], then

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two-photon pick-off annihilations may be used to determine the annihilation time and position for each event, which in coincidence with the registration of prompt gamma would allow to determine lifetime spectra for each voxel and hence to reconstruct the ortho-positronium lifetime based on two-photons pick-off annihilations which for the human body (with the orthopositronim lifetime of about 2 ns) are about 70 times more frequent than three-photons events. Therefore, the proposed method of positronium imaging shall become feasible in the future with the advent of total-body PET and improved time resolutions. Moreover, recent theoretical studies [12] have proven that the entanglement in the three-photon state originating from the decay of ortho-positronium survives surprisingly also for mixed scenarios expected in human tissues. Hence, detecting entanglement of the three-photon state may enable the extraction of quantum information in the form of distinct features from metabolic processes in human bodies. Entanglement of photons originating from positronium decays can be detetermined by the measurement of photons polarization.

Jagiellonian-PET (J-PET) collaboartion conducts research aiming at the elaboration of the cost-effective total body PET which will be built from plastic scintiilators [13]–[16]. For details about front-end electronics, data acquisition, data anaysis and reconstruction methods the interested reader is referred to references [17]–[20], [22]–[25]. J-PET solution enables production of modular, light and portable tomography systems, which can be adjusted to the size of the investigated patient. Possibility of constructing the tomograph from light and portable modules may expand the current applicability of PET beyond staging patients to help diagnose diseases in large animals or to expanding the use of tracer imaging in botanical sciences. J-PET tomograph enables also measurements and imaging of the properties of positronium atoms [1] including quantum entanglement of photons originating from the positronium decay [2], [12], [26].

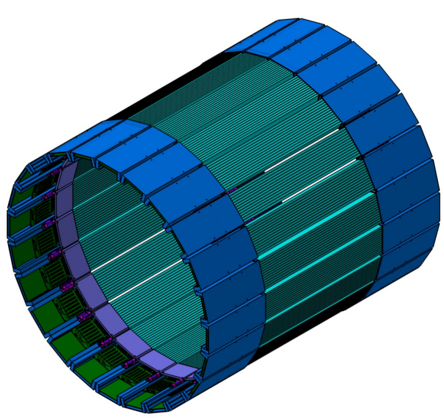

Fig. 1. Schematic view of the modular J-PET tomograph built from 24 modules.

II. Methods and Results

We explored the possibility of performing positronium imaging using dedicated Monte-Carlo simulation procedures which are described in detail in references [1], [7], [23], [27].

We have also conducted feasibility studies of the measurement of polarization of annihilation photons with the J-PET tomograph [2]. J-PET is built from plastic scintillators [14]–[16], [21] in which annihilation photons interact predominantly via Compton scattering. Registration of both primary and scattered photons enables to determinate the linear polarization of the primary photon on the event by event basis [25] and hence enables to witness the entanglement of annihilation photons in polarization based on Mutually Unbiased Bases [26]. Detailed results of the feasibility studies of the polarization of annihilation photons with the J-PET tomography scanner are presented in reference [2].

The simulations are carried out assuming an ideal case, that the scanner is built from four concentric layers of axially arranged plastics scintillator strips adjacent to each other. In order to reconstruct a mean lifetime of ortho-positronium atoms in each voxel of the patient it is necessary to identify events with ortho-positronium production and for each such event to determine the time of the ortho-positronium creation and decay. Simulations of orthopositronium formation and its annihilation into three photons were performed taking into account distributions of photon's momenta as predicted by the theory of quantum electrodynamics and the response of the J-PET tomograph. In order to test the proposed ortho-positronium lifetime image reconstruction method we concentrate on the decay of the ortho-positronium into three photons and applications of radiopharmaceuticals labeled with isotopes emitting prompt gamma. The annihilation point and time of $e^+e^- \to 3\gamma$ processes is reconstructed in an analytical way based on the measured times and positions of the three photons and knowing that (due to the momentum conservation principle) all three photons momentum vectors and the annihilation point are lying in a single plane, referred to as a decay plane [7]. As a result we have established that assuming a coincident resolving time of the detector of 140 ps it is possible to achieve resolution of about 40 ps for the determination of the mean lifetime of ortho-positronium atoms [1]. We have also established that the J-PET tomograph built from plastic scintillators enables to determine relative angle between orientations of the annihilation photons' orientations [2].

As a pilot studies of testing the possible correlation between the positronium properties and the grade of the tumors, we have studied lifetime of positronium and its production probability in the cardiac myxoma tumor surgically resected from the left atrium of the heart of 72 years old women [29]. The patient was operated in the Hospital in Cracow and the research with the tumor was conducted under the ethical approval. Cardiac myxoma is a primitive connective tissue tumor. It is a neoplasm composed of stellate to plump, cytologically bland mesenchymal cells set in a myxoid stroma [29]. The parts of the tumor were cut into about 2mm thick slices and inserted in the containers. We prepared a special ^{22}Na radioactive source closed in a 7μm thin kapton foils which was placed between two slices of the tumor. The results from various samples are consistent and show that the ortho-positronium production intensity in the investigated tumor is equal to about 25% and the ortho-positronium lifetime amounts to about 2.1 ns. We have also performed studies with normal and diseased tissues in samples of uterine leiomyomatis and normal myometrium tissues taken from women-patients after surgery of uterous tumors [4]. For all six studied patients it was found that the values of the mean ortho-positronium lifetimes are about 2 ns, and that they are larger for the tumorous tissues than for the healthy ones by about 50ps. At the same time, the intensity of positronium production was found to be smaller for altered tissues than for the normal ones [4].

III. Conclusions

Pilot investigations of properties of positronium atoms in uterine tissues operated from human patients indicate meaningful differences between healthy and tumorous tissues. The obtained results [1] show that, as suggested in references [6], [28], measurements of properties of ortho-positronium atoms (such as lifetime and production probability, or 3γ to 2γ rate ratio) which are formed inside the human body during a routine PET imaging may deliver information useful for the diagnosis. The feasibility studies of the imaging of positronium properties [1] show that it is possible to obtain such images with the future total-body PET modalities. We have shown also that the J-PET tomograph is capable of determining quantum entanglement of photons from the decays of positronium atoms [2]. The first indications of the differences of positronium properties in healthy and cancerous tissues are promising, however there is still a long way to the future clinical application of positronium imaging which requires longstanding and systematic studies in order to verify: whether positronium properties (i) differ in healthy and cancerous tissues?, (ii) vary with the type of the cancer?, (iii) depend on malignancy grade for a given cancer type, and whether and to what extent positronium properties in a given cancer type are patient dependent.

Acknowledgments

We acknowledge the Foundation for Polish Science through MPD and TEAM/2017-4/39 programs, the National Science Centre through grant Nos. 2016/21/B/ST2/01222, 2017/25/N/NZ1/00861, the Ministry for Science and Higher Education through grant Nos. 6673/IA/SP/2016, 7150/E-338/SPUB/2017/1, the EU and MSHE grant No. POIG.02.03.00-161 00-013/09.

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