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Positronium and Quantum Entanglement Imaging: A New Trend in Positron Emission Tomography

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***Abstract*—We report on the progress in the development of *positronium imaging* and quantum entanglement imaging achieved thus far by the J-PET collaboration. Positronium (a bound state of electron and positron) is copiously produced in the human body during positron emission tomography. Its properties depend on the size of the intra-molecular voids and concentration in them of molecules as e.g. molecular oxygen. Therefore, positronium may serve as a biomarker of tissue pathology and hypoxia. Recently, the positronium imaging method was developed and the first positronium images of phantoms comprised of tumor cardiac myxoma and healthy adipose tissues were created by means of the J-PET tomograph. A significant difference in mean positronium lifetime in cardiac myxoma and adipose tissues opens promising perspectives for the application of positronium as a cancer diagnostic indicator. It is also important to note that photons originating from the decay of positronium are quantum entangled in polarisation. Thus, it can be hypothesized that by measuring the degree of entanglement of photons from positronium annihilation, additional information can be obtained about the molecular environment in which the positronium is formed. J-PET is the first PET system enabling the determination of linear polarisation of annihilation photons. The measurements performed with the J-PET detector confirm that the distribution of relative angle between the polarization of 511 keV back-to-back photons is consistent with the assumption that these photons are quantum entangled. These results open up prospects for the study of quantum entanglement of photons from positronium annihilation in living organisms.**

I. Introduction

THE main objectives of the presented research are the development of the positronium imaging method [1], [2], [3], [4], [5], [6], and the assessment of the diagnostic potential of positronium applications as a biomarker of tissue pathology [6], [7], [8], [9]. Positronium is a bound state of positron end electron that is also abundantly produced in the inter- and intra-molecular spaces in the organism subjected to Positron Emission Tomography. Properties of positronium such as e.g. mean lifetime and production probability depend on the size of intra-molecular voids and on the concentration in them of free radicals and paramagnetic molecules playing a role in cellular metabolism. Therefore, positronium may be used as a hallmark of the molecular environment in which it is formed. To translate positronium imaging into clinical diagnostics, two independent research challenges need to be addressed. Firstly, a method for the spatially resolved in-vivo reconstruction of positronium properties needs to be developed (referred to as positronium imaging [2]), and secondly, correlations between these properties and the type and degree of tissue pathology need to be established. There are three well-established characteristics of positronium that are of interest for the biomedical applications. These are mean lifetime (τ) distribution, production probability (P) distribution, and the ratio (R) of 3-photons to 2-photons decay rates. It is also conceivable that the degree and a type of quantum entanglement of annihilation photons, expressed as a value of entanglement witness (Q), may be used as a diagnostic biomarker [11], [12]. Importantly, the ratio R and quantum entanglement witness Q, require registration of annihilation photons only and may be established for all kinds of β+ isotopes applied in PET diagnostics, such as e.g. most commonly used ^{18}F which emits only positron. However, for the reconstruction of a mean lifetime (τ) and production probability (P), a positron lifetime spectrum needs to be established which requires determination of the time of positron emission and the time of its annihilation [3], [4], [6]. This can be achieved when applying $\beta + \gamma$ isotopes, as e.g. ^{44}Sc. The $\beta + \gamma$ isotopes in addition to positron emits prompt photon γ via reaction chain $^{44}\text{Sc} \rightarrow ^{44}\text{Ca}^{*} + e^{+} + \nu \rightarrow ^{44}\text{Ca} + \gamma + e^{+} + \nu$ [13], [14]. Registered time and position of the interaction of annihilation photons are used for the reconstruction of the time and place of annihilation, while registered time and position of prompt photon interaction enables to reconstruct the time of the emission of a positron. Reconstruction of any of the mentioned characteristics (τ,P,R,Q) requires measurement of more than two photons, and therefore current PET systems optimized for the registration of 2-photon electron-positron annihilation cannot be used for this purpose.

II. J-PET: multi-photon PET system

J-PET collaboration is developing a cost-effective and high-sensitivity method for the multi-photon (two and more photons) total-body imaging [15], [16], [17], [18], [19], [20], [21], [22], [23]. So far two system prototypes have been constructed and commissioned for PET and positronium imaging [24], [25]. Reconstruction of the annihilation place, in the case of 2-photon and 3-photon annihilations, is based on the measurement of the positions and times of photons' interaction in the tomograph [3], [4]. J-PET prototypes are built from strips of plastic scintillator, forming a cylinder [24], [25]. The position and time of reaction of photons along the scintillator strips are determined based on the time of arrival of light signals to the ends of the scintillator strips [16]. The electric signals are

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probed at four voltage thresholds [26] and the digitized signals are collected by the trigger-less data acquisition system [27]. The collected data are filtered and analyzed using a dedicated software J-PET framework [28].

III. Results

Recently, first in-vitro positronium images of phantoms consisting of cardiac myxoma tumor tissues and healthy adipose tissues have been obtained [6], proving that J-PET is capable of a simultaneous standard 2-photon metabolic imaging and positronium imaging [6]. The first positronium images [6] are based on the 2-photon pick-off annihilations of ortho-positronium that is in the tissue about 70 times more frequent than the ortho-positronium 3-photon self-annihilation. The sensitivity of the PET system decreases with the growing number of coincidently registered photons. However, based on the Monte-Carlo simulations, it was shown that the total-body J-PET sensitivity for 2-photon positronium imaging is even a few times larger than the sensitivity for standard PET imaging with a PET system of 20 cm long axial field-of-view [8], [29]. Using the J-PET tomography prototype we have also determined a first 3-photon annihilation image of the cylindrical phantom [5]. This 3-photon annihilation image was reconstructed by means of the trilateration method [30]. It was also shown that the mean lifetime of ortho-positronium differs by about 700 ps between cardiac myxoma and healthy adipose tissues [6], [9], [31] giving a promising perspective for applications of positronium as a biomarker for tissue pathology, and indicating that the differences in positronium lifetime are due to the nano-structural differences between these tissues rather than due to the differences caused by conversion on oxygen molecules. The latter is expected to change the mean ortho-positronium lifetime by a few picoseconds only [32], [33].

Moreover, it is also conceivable that entanglement in the three-photons originating from annihilation of ortho-positronium may enable the extraction of quantum information about the molecular environment in the tissue, where the positronium is formed, provided that entanglement of three-photon states survives for the mixed states scenarios expected in human tissues. Yet, this has to be verified experimentally, especially that the theoretical predictions differ between each other [11], [34]. J-PET tomograph, built from plastic scintillators in which annihilation-photons interact predominantly via Compton scattering, enables to determinate the linear polarization of the primary photon on the event by event basis [35] and hence enables to witness the entanglement of annihilation photons based on Mutually Unbiased Bases [12]. Entanglement of photons originating from electron-positron annihilations is also studied in view of the improvement of PET imaging quality by the reduction of scatter and random coincidences. Recently it was shown [36] that distribution of the relative angle between polarization directions of photons from the 2-photon annihilations is enhanced at 90 degrees with the strength as predicted for the entangled photons. The above discussed emerging methods of positronium imaging, and research towards the application of quantum entanglement in PET, require high sensitivity and high time resolution of PET systems. These are now becoming achievable with the advent of the total-body PET systems [8], [29], [37], [38] and constantly improving time resolution [39], [40].

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