International workshop ”Positronium - from Quantum Physics to Medical Applications”

Wednesday, 26 April 2023 - Friday, 28 April 2023

Split, Croatia

Book of Abstracts

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Welcome and registration

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Opportunities to do experiments in an underground laboratory

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I shall discuss opportunities to do underground experiments by presenting our investigations of possible departures from the standard quantum mechanics'predictions at the Gran Sasso underground laboratory in Italy.
In particular, with refined radiation detectors we are searching signals predicted by the dynamical collapse models (spontaneous emission of radiation) which were proposed to solve the "measurement problem"in quantum physics, and signals indicating a possible violation of the Pauli Exclusion Principle.
I shall discuss our recent results which ruled out the natural parameter-free version of the gravity-related collapse model. I shall then present more generic results on testing CSL (Continuous Spontaneous Localization) collapse models and discuss future perspectives.
Finally, I shall briefly present the VIP experiment, with which we look for possible violations of the Pauli Exclusion Principle by searching for "impossible"atomic transitions, and comment the impact of this research in relation to Quantum Gravity models.
I shall take this opportunity to stimulate discussions about possibilities to use positronium in future underground experiments.

Positronium in fundamental investigations / **3**

Positronium imaging with modular J-PET for medical diagnostics and basic research in physics

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The Jagiellonian Positron Emission Tomograph (J-PET) is the first PET scanner based on plastic scintillators.
It is designed to measure momentum vectors and the polarization of photons originating from the decays of positronium.
In combination with the newly invented positronium imaging method, J-PET enables the study of discrete symmetries in positronium without the use of magnetic fields. We will present the latest results of P, T, CP, and CPT symmetry studies with the J-PET detector (Nature Communication 12, 5658 (2021)) as well as explain the method of positronium imaging that enables imaging of positronium properties in living organisms (Science Advances 7, eabh4394 (2021), Nature Reviews Physics 1, 527 (2019)). In the talk, the method of positronium imaging in living organisms and the first in-vivo positronium images of humans obtained with the J-PET tomograph will be also presented and explained.

Positronium in medical imaging / **4**

Nuclear medical imaging based on entangled photon pair

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Research activities related to novel nuclear medicine instrumentation in the university of Tokyo will be introduced. Especially Compton and PET hybrid scanner, quantum entanglement PET and simultaneous imaging and sensing based on cascade entangled photons will be discussed together with its readout electronics and image reconstruction.

Positronium in fundamental investigations / **5**

Quest for High Energetic Entanglement from Positronium Decays: A Rigorous Study

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Recently, theoretical and experimental papers have been published that put forward different interpretations about the physics of the photons produced in positronium decay. Most of the publications claim that their data prove quantum entanglement. This talk will give an overview of the underlying assumptions and the prospects of the upcoming experiments.

Positronium in medical imaging / **6**

Nanoparticles for theranostics with PET and MRI

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In nuclear medicine, cancer theranostics refers to the strategy of combining diagnostic imaging with targeted therapy. In this talk, I will discuss how theranostic efficacy may be enhanced by leveraging the unique properties of nanoparticles. Due to their nanoscale size, nanoparticles can penetrate target tissues and tumour cells, and enhance physico-chemical reaction rates. Additionally, nanoscale geometric confinement confers unique physical properties. Superparamagnetic nanoparticles, in particular, offer a unique platform for radiolabelling with PET isotopes, while also enhancing contrast in Magnetic Resonance Imaging (MRI). Additionally, such nanoparticles, when radiolabelled with a therapeutic isotope, can enhance localised damage to tumour cells, thereby improving therapeutic outcomes.

Positronium in medical imaging / **7**

Development of Compton-PET hybrid camera for multi-tracer imaging in nuclear medicine

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Simultaneous imaging of PET (positron emission tomography) and SPECT (single photon emission computed tomography) nuclides is difficult in commercial nuclear medicine imaging systems due to their different principles, such as the presence or absence of mechanical collimators. We have proposed Compton-PET hybrid imaging system, which can perform simultaneous PET and SPECT

nuclides imaging by the conventional PET and Compton imaging, without any mechanical collimators. We have developed some prototype cameras using different detectors, such as GAGG-SiPM (silicon photomultiplier) detectors, CeBr3-SiPM detectors and silicon detectors. In the presentation, we will introduce the detail of our imaging system and demonstration results.

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Single Layer Gamma-Ray Polarimeter for Medical Imaging Applications and Fundamental Physics Research

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We will present an overview of the activities undertaken with the experimental system based on single layer gamma-ray polarimeter. This modular system consist of 16 position sensitive scintillator matrices read out by silicon photomultipliers. We have shown that these simple detectors can successfully measure the polarization of gamma rays via internal Compton scattering. Owing to its modularity the system can be exploited in various setups in fundamental research and medical applications. We will present three such setups: the first one for the measurements in Positron Emission Tomography, where the benefit of using the gamma-ray polarization was investigated, the second where the implications of decoherence of annihilation quanta were explored and the third, where triple-coincident measurement of gamma rays from ortho-positronium decay were done.

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Investigation of decoherence of annihilation quanta

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Recently, different groups have performed measurement of polarization correlations of annihilation quanta after inducing decoherence of one of the gammas by Compton scattering yielding somewhat contradictory results. Watts et al. [Nat. Commun., 12, 2646, (2021)] reported the result hinting at loss of correlation, while Abdurashitov et. al. [Jour. Inst. 17, P03010, (2022)] reported strong correlation at least at small scattering angles. We have used the setup based on Single Layer Gamma Ray Polarimeters to measure the correlation of annihilation quanta after an intermediate Compton scattering under angles ranging from 0 to 50 degree, thus significantly extending the range compared to previous measurements. The results of these investigations will be presented.

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Investigation of a Single-plane Compton gamma camera as a radiation imager

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Radiation imaging and detection is an outstanding topic in various areas from astroparticle physics, over medical imaging to radiation security. On of suitable detectors which has been researched lately is the Compton camera offering potential advantages such as a wide field of view, the ability to reconstruct 3D images, and with a portable lightweight design due to absence of heavy collimation. We designed and constructed a novel, compact Compton gamma camera whose detector element consists of two scintillator crystals optically coupled by a light guide between them. We used GAGG:Ce scintillators of 3 x 3 x 3 mm3 and 3 x 3 x 20 mm3 plexiglass lightguides. Detector elements were placed in an 8 x 8 matrix with a 3.2 mm pitch, separated by ESR reflector. In this configuration the front scintillator layer is acting as the scatterer and the back scintillator layer is acting as the absorber of the Compton scattered gamma radiation, while both are read out by the same silicon photomultipliers (SiPM) array coupled to the back side of the matrix, thus forming a compact single-plane detector. We will report the results of the performed laboratory characterization of the detector.

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Development and characterization of the PET demonstrator with measurement of polarization correlations

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Positronium in fundamental investigations / **12**

Search for the CP symmetry violation in the OPSVIO project

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One of three Sahkarov conditions needed to explain the matter-antimatter asymmetry problem is the existence of CP symmetry breaking. This was indeed observed in the quark sector but with the magnitude which is not large enough to solve the matter-antimatter asymmetry problem. Since the CP violation is allowed by some leptogenesis models, the search for additional CP symmetry breaking was extended to leptonic sector. A recent experiment involving neutrino oscillations reported the indication of CP violation but with no decisive conclusion.

A complementary approach to search for the CP violation in leptonic sector is to use the tensor polarization of ortho-positronium (o-Ps) induced by an external magnetic field and measure the angular distribution of produced gamma rays. More than one-decade old result showed that there is no CP violation in o-Ps decay at precision level of 10–3. In this presentation we will present the experimental set-up of the OPSVIO project with which we plan to improve the precision level for one order of magnitude compared to the state-of-art result.

Positronium in fundamental investigations / **13**

Measurements of the polarization of photons in ortho-positronium annihilation

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An overview of the previous measurements of the polarization of photons in positronium annihilations, with special emphasis on ortho-positronium annihilations, will be given. Possibilities for the measurements of the polarization of all three photons in ortho-positronium annihilations with single-layer Compton scattering detector systems developed at the Department of Physics in Zagreb as well as the first measurements will be presented.

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An overview of basic concepts and formulas in simulations of the Compton scattering

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We give an overview of basic concepts and formulas used in simulating the Compton scattering. Special emphasis is given to a Klein-Nishina expression for a differential scattering cross section for a single photon. In a context of entangled annihilation photons, a scattering of single (uncorrelated) photons is a reference point for gauging the quantum effects due to the entanglement itself. As such, the uncorrelated scattering of multiple photons must be perfectly characterized when analyzing the experimental data pertaining to the entangled photons. In that, an experimental evidence for the photon entanglement and its effect upon subsequent scattering is to be found in the observed deviations from the uncorrelated scattering.

Positronium in medical imaging / **15**

Recent advances of positron emission tomography image reconstruction

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Positron emission tomography (PET) is a widely used imaging modality that enables the non-invasive visualisation of physiological and biochemical processes in living organisms. However, PET images are inherently noisy and suffer from low spatial resolution, which can limit their diagnostic accuracy

and clinical utility. To address these challenges, numerous image reconstruction methods have been proposed and developed over the past years.

In this presentation, we will discuss the recent trends in PET image reconstruction, focusing on techniques designed to improve image quality, allow the reduction of the injected radioactive dose as well as the acquisition time. Specifically, we will cover dynamic and quantitative PET imaging, total-body PET, time-of-flight (TOF) technology, resolution recovery. Finally, we will discuss the challenges and opportunities in using artificial intelligence (AI) and deep learning (DL) for PET.

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Enhanced Positronium formation and Annihilation Localization with nano-scale magnetization

Developments in radiolabeling superparamagnetic iron oxide nanoparticle (SPIONs) have gained increasing attention for cancer theranostic applications1. In a previous study, we demonstrated that the FDA approved SPION Feraheme® (FH) can be radiolabeled with a range of therapeutic and diagnostic isotopes: 64,67Cu, 90Y, 177Lu, 89Sr, 140Ba, 99Mo, 212Pb, 213Bi, 111In, 153Sm, 161Tb, 156,157Eu by the chelate-free heat induced radiolabeling technique2. In separate studies, we also demonstrated that radiolabeled FH can enhance dose deposition3 and that 89Zr-FH is a highly suitable radio-nanoplatform for hybrid PET- MR imaging4. Here, we investigate for the first time the effect of magnetized radiolabeled FH SPIONs on dose localization and positron range, as well as and ortho-positronium production from 89Zr-FH.

A series of [Fe] dilutions of 89Zr-FH samples was prepared in 10 separate phantom vials (including only 89Zr). The activity in each phantom was kept constant, A0 = 3.7 kBq. The phantoms were scanned using a simultaneous clinical PET-MR scanner (3T Biograph mMR). The full width at half maximum of the line spread function were calculated for the PET image data to assess the impact of magnetized FH SPIONs on the spatial resolution. The integrated standard value uptake for a circular region of interest for each phantom scan was calculated to quantify the dose localization.

Results demonstrated the magnetized FH SPIONs improved the spatial resolution of the 89Zr-FH phantom PET images by ≈ 17± 1.6 %, localized the dose by ≈ 40 ± 0.9 % and increased the true and random counts by ≈ 6% and 1% respectively, at a clinical [Fe] FH dose level. Both improvements in spatial resolution and dose localization are due to the nano-scale enhanced magnetic field induced by magnetized FH SPIONs and this has been further confirmed by PET-MR image analysis. In a clinical scenario, enhancing dose localization by 40% may improve the tumor control probability by 40%. Furthermore, the increase in true and random counts may be due to the interaction of positrons within the 89Zr-FH solution resulting in annihilation via formation of ortho-positronium (in the triplet state, 3S1) and emission of three gammas. Thus, this study further suggests radiolabeled SPION can enhance the production of ortho-positronium. Such triple-coincidences may be processed as a set of double coincidence events by the PET scanner. It would be interesting to follow up our study using emerging total body PET scanners, which with their superior sensitivity and 4π geometry are ideal for triple coincidence detection and potentially for ortho-positronium emission tomography.

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Medical physics in everyday practice of nuclear medicine

Short overview will be given of the possible activities of medical physicist (MP) in nuclear medicine (NM). Starting from various aspects of radiation protection issues stemming from the fact that nuclear medicine deals with open radioactive sources (radiopharmaceuticals). Quality control of instruments such as gamma camera and PET scanner are also an important part of the routine job of MP. Few examples will be given of how MP can apply mathematical modeling and sophisticated software to improve both diagnostic and therapeutic procedures in NM, thus helping medical doctors in solving important clinical questions.