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Evaluation of Doctoral Thesis of mgr Kamil Dulski, entitled „Development of positronium imaging with the 192-strip J-PET detector".

Education

Mgr Kamil Dulski delivered, in date Dec. 21st. 2021 the Doctoral Thesis entitled as above, on the novel type of Positron Emission Tomography (PET), where J stays for "Jagiellonian".

Mgr Kamil Dulski, born in 1992, studied in 2011-2016 Advanced Material and Nanotechnology at Jagiellonian University, with Bachelor Thesis on J-PET polymer scintillators and with Master Thesis on assembling and calibration of the apparatus on positron annihilation lifetime spectroscopy.

In the period overlapping with the studies at the Faculty of Physics UJ, in the period 2015-2017, he studied at the Faculty of Mathematics and Applied Computer Science UJ, specialization in Biomathematics, with the Bachelor Thesis on tensor product, and master thesis on compressive sensing and signal compression.

In 2016 mgr Kamil Dulski entered Biophysical doctoral studies at Faculty of Physics, Astronomy and Applied Computer Science at UJ.

Judging these courses, and the numerous experimental and numerical skill resulting from his cv, his overall education was highly complementary, that explains also the multi-task achievements reported in his Doctoral Thesis.

Doctoral Thesis – scientific contents

The Doctoral Thesis consists of six chapter plus ten appendices, 159 page in total. It is written clearly and thoroughly printed.

The long-term aim of the PhD work by Mr Dulski is to contribute to the construction of an innovative Positron Emission Tomography device, called J-PET. The leading expression is "whole-body PET". This could be, in principle obtained by multiplying the gamma detectors and attached to them photomultipliers as in commercial PETs, but the cost (and the operation) of such a device would be prohibitive.

The innovative elements in J-PET as compared to standard PET devices currently in use are four-folds:

- the use of long (body-length) and cheap polymer-strips instead of BaF_2 detectors (the latter with few squared centimeters detection area)

- following from this, the use of (low-cost) silicon light detectors (instead of costly dynode-based photomultipliers)
- the aim to distinguish three-gamma (i.e. ortho-positronium) decays, what in turn may bring information both on morphology of the annihilation site and the chemical environment (the presence of oxygen quenching o-Ps and other information)
- innovative, ultra-fast electronics permitting in real time the selection of useful signals.

These four innovative elements are interlaced: the signals from polymer detectors, in principle, are of worse time resolution then from BaF_2 (or other similar) detectors, multiple scattering of the light inside the wave-guides formed by the polymer strips gives additional arrival times/ and or signals, and further, differently from two-gamma annihilation in classical PETs, the o-Ps does not yield well-defined energies and directions of gamma signals appearing. Additionally, in order to compete with the present (c.a. 2 mm in diameter) resolution of commercial PETs, the J-PET must resolve the major problem of time and space resolution.

All these elements of the scientific novelty of J-PET result clearly from the totality of the PhD Mgr Kamil Dulski, even if he does not present the achievement in this way (he is far more modest). Mgr Dulski achieved the scientific goal: separate arguments are treated in his PhD in appropriate places, and contributions of other co-workers of the J-PET (detectors, scintillators, phantoms etc.) are correctly described, mainly by calling their work in the references.

<u>Detailed contents</u>

In the introduction mgr Dulski writes "The main objective in the development fo the PET scanners is to improve quality of the obtained images […]". As I wrote above this is a very modest statement. The innovative goal of J-PET is to use the spectroscopy of positronium, what is completely new detection channel for PET. The Authors says this in a sentence about "patient's metabolism" (page 9, line 6 from bottom).

The very aim of the PhD work is stated in page 10: "a very good time resolution of the detectors (in the order of 100 ps) to properly estimate positron lifetime and have data acquisition system to detect multiple photons coming from a single event." Further Mr Dulski states that the lifetime of positronium "is also an extremely sensitive structural indicator in materials research." It is somewhat pity that he recalls only rather monothematic references [25-29] in support of this statement.

Charter I is somewhat weaker than the rest of the dissertation. The candidate discusses the model of "free-volumes" as seen by measuring the o-Ps annihilation fractions. This is rather old (Tao/ Eldrup 1972/1980) model, that worked well in some "textbook" cases, like porous glasses, i.e. materials with he same chemical lining and only different morphology. A number of works was done from the times of Tao and Eldrup, I nominate only the experiments (and models) by Consolati, and recent work on the matching between p-Ps and o-Ps annihilation lifetimes by Tanzi Mariotti. Applying models that may be inadequate to the main problem of the Thesis, i.e. the all-body PET, could be scientifically misleading. However, this is the indication for the future work, that may improve the analysis of the results obtained also in the PhD dissertation.

Similarly the statement on the domination of the Ps formation preferentially in so-called Ore's gap is not confirmed by recent direct experiments and/or theories on positron interaction with molecules (see model works by Fursa and collaborators on H_2 or the whole series of experiment on Ps formation by Kauppila and Stein group). When speaking about spur and bubble the reference given [51] dates to 1957. There are several (Monte Carlo) models analysing in detail the energy loss by positrons injected into matter (Gustavo Garcia and similar). Again, the Candidate was not obliged to follow all these developments, that come from Atomic Physics rather than from Solid State Physics.

The last part of the 1st Chapter, par. 1.5 clearly describes the principle of positron emission tomography as medical diagnostic tool. A next novel element to the innovative scheme of J-PET is the proposal to use the ^{44}Sc isotope (instead of ^{18}F) for positronium imaging.

Chapter II describes J-PET prototype detector, which is already operative. The introducing of the J-PET is done step-by-step, clearly, or I would say, even didactically. The author describes the experimental set-up and principle of measurements (that lasted 27 days for one sample). Advanced, on-purpose software J-PET Framework was used for data acquisition.

On page 30 the sample used for the calibration "porous material XAD4" is nominated. It is pity that no details were given, what would facilitate the evaluation of the lifetime results obtained by the Author.

Generally, this chapter, even if concise, is clearly written and enough informative.

The chapter III describes the work by Author in the subject of time resolution. The main difficulty in positron lifetime measurements is a correct detection of two signals separated as little as some 100 ps. The intrinsic time resolution of the fastest detection chains presently used (i.e. the scintillator, the photomultiplier and the electronic analyzer) rarely exceed 180 ps. The crucial point is the choice of the thresholds: the calibration along the plastic strips of detector is discussed in par. 3.1 and of calibration of positron lifetime in par. 3.2. The latter question is also the object of one patent (Dulski & Moskal). These two calibrations serve as the starting point for the whole J-PET: the successive iterations of the calibration procedures gave improvement by 200 ps steps. The obtained space resolution of the position along the strip is 3.029(75) cm.

On page 54 the given light velocity in the scintillators is related to their refraction coefficient, I suppose?

Chapters IV and V are the most important, showing (even if the Author does not say it openly) an absolute scientific breakthrough. This breakthrough is not finding the new phenomena, neither new measurements, but the extremely tedious analysis of the very feasibility of the space-resolved analysis of the o-Ps (and p-Ps) lifetimes, in non-homogenous samples (like the human body). The level of understanding the problem proves the decisive contribution of the Author to solving this question.

Chapter IV discusses the particular novelty of J-PET, i.e. the aim to detect three photons coming from o-Ps decay. Presently used PETs detect only two co-linear photons from the direct annihilation or from the para-Ps. In these cases the reconstruction of the annihilation site is easy: it is enough to find the straight line. In case of thee gamma they are neither co-linear nor bring 511 keV energy: the geometry is complex and the detection thresholds to impose are, a priori, unknown.

Author worked both on algorithms and tested “commercial” lifetime analysis packages with measurements in hexane. He used data similar to experimental (table 4.1) for successive simulations. His conclusion on the analysis, on page 64 are “non-orthodox”, i.e. novel and particularly useful for J-PET.

Chapter V starts from the discussion of multi-scattered gamma photons (in the three layers of plastic strips) that can bring spurious signals, being classified as annihilation event, and vice versa (real events classified wrongly as scattering events). The Author tested the question comparing lifetime measurements from J-PET on a porous sample (XAD4) with standard measurements in laboratory system. This is a great idea, however in order to judge on the quality of result (table 5.1) some details of the laboratory system [29] would be useful.

The space-time deconvolution is done by steps. First by considering the relations between angles at which gamma photons have been detected (fig. 5.5), next by rejecting events from two adjacent scintillators (fig. 5.6), and finally by the analysis of lifetime spectra.

Particularly difficult is the lifetime deconvolution task, like fig. 5.8, where as many as seven components are analysed: the result is, for me, convincing. Note that in “standard” lifetime measurements going already into four components becomes risky without any pre-measurements indications. Correlation coefficients given in table 5.2 are fairly good. The cosmic background was measured in a separate, shorter (66 hours) run. Finally, in fig. 5.10 the experimental lifetime spectra decomposed into two and three gamma events are compared with simulations.

An unexpected “by-product” of the tests is the precise measurement on the o-Ps lifetime in vacuum, with as many as five significant digits, 142.046 (14) ns (vs. 142.05 ns theoretical value). This in not only the result itself, but also the showing the utility of J-PET for fundamental physics.

The theoretical reference to free-volumes in inorganic materials comes back in Chapter V (p. 80) but this time the Author is aware the o-Ps lifetime may be related to oxygen contents, even if the given references [63, 79-82] are not the most novel neither the most representative. The Author/ Team should update their knowledge in this subject.

On page 91 the Author correctly stated that the probability of pick-off process may depend on time, i.e. on positronium velocity. Again, the references given [114-117] are not incisive: the Author should enlarge the search into the field of direct experiments (and theories) on Ps scattering (Gaetana Laricchia, Ilya Fabrikant).

Chapter VI describes test on sample, “IC3100”, “XAD4”, PVD and on two biological tissues. Data selection and the reductive procedures to minimize the voxel for the space resolution are described . The result of the fitted lifetimes from the three samples (table 6.1) are to be considered quite satisfactory, given the complexity of the problem. The figure 6.5 gives the mean o-Ps lifetime for the three porous samples, 2.02 ns, 25.8 ns and 51.4 ns. At this stage (fig. 6.6) the use of the simplified models (Tao-Eldrup and Goworek) is also justified. Quite promising is also the feasibility to distinguish lifetimes in two biological tissues (fig. 6.7). Again the results may be improved, like the percentage of the source contribution, table 6.2, which should depend on the atomic numbers of the material surrounding the radioactive source; and again, this was not the task of the Candidate.

Appendices describe in detail the calibration methods (A), iterative corrections of the calibration (B), determination of the effective length (C), z-position resolution (D), generalization of the reconstruction algorithm (E), three-photon reconstruction (F), artifacts in angular distribution (G), step-by-step reconstruction of the annihilation position (H), the analysis for porous phantoms (I) and tissue samples (J) – the two latter the most comprehensive. The appendices are rich in illustrations which are real experimental data collected and analyzed.

The references quote 130 positions, pretty recent and well chosen. No excessive self-citations.

Formal lay-out

The Thesis is extremely well published. In particular, step-by-step schemes and analysis of experiments done by the Candidate are of excellent quality and clarity. The overall impression is very high. Writing the Thesis in English is important, as many of the subjects are new on the global level, and are worth divulgating.

A minor note is that the English is somewhat difficult to read. However, the scientific transmission is clear.

Page 15 discusses the energy-loss processes of positron injected into matter: this is electronic (and vibrational and rotational) excitations (not “excitement”). The same page, last paragraph should read: “terminal state” (not “phase”).

In Polish, streszczenie (“z powodzeniem rozdzielając różne typy tkanek”) should read “z powodzeniem rozróżniając”.

The Author makes frequent referring to previous or next paragraphs: the attentive referee knows the links by himself/ herself. Sometimes the Authors uses his research group short-cuts, like “IC31000 [118], XAD4 [94]”, when describing the test samples (p. 95).

Absolutely extraordinary, textbook-like are the graphical representations and schemes.

It is also absolutely needed to stress that this great amount (and variety) of data presented are the experimental results obtained with the participation of the Author, and by him analysed.

Conclusions

The thesis by Mr Kamil Dulski deals with a really advanced physics. It proves also that the two fields – fundamental and applied science are commonly interlaced: the job aiming to the construction of a new type PET led to the measurements of the fundamental constants of quantum electrodynamics like the o-Ps lifetime in vacuum.

The main subject of the whole Thesis (and the main contribution of the Candidate to J-PET) is finding the ways to perform the correct detection and timing of the annihilations signals. This is really a challenging task.

The Candidate resolved, I would say, in a master way the aims that were posed in his PhD (and which result from the functional work division in the J-PET group, I suppose). He did not entered into details of positron lifetime measurements in a "single-point" condition, but using simplified methods he proved the feasibility of the main J-PET aim: a space-resolved spectroscopy of the o-Ps (i.e. three gamma) annihilation.

The Author resumes this achievement on page 108, writing: "It is worth mentioning that positronium imaging does not require additional mechanical modules, but only consists in appropriate energy selection of photons and the possibility of measuring the time of photon arrival."

The Author is also aware that simplified model of porosity (of inorganic samples) is not adequate for biological tissues: "It is difficult to talk about any pores in tissues […]" (p. 109). This certifies the ability of the Candidate in critical thinking, and thus for the future development.

Some criticism that my evaluation seems to contain comes exclusively from the exceptionally high level of the PhD dissertation presented (as long with the publication record of the Candidate): it is worth to indicate further ways of the development, in the subject which is extremely innovative, and therefore not free from risks of misinterpretations.

In conclusion I state that the Doctoral Thesis and the overall scientific profile of mgr Kamil Dulski follows the criteria established by Polish "Ustawa o stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki" (Dz. U. z 2016 r., poz. 882).

In a separate statement I postulate to award this Thesis *cum laude*.

Toruń, 18 February, 2022.

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