

CONSTRUCTION OF THE VACUUM CHAMBERS FOR J-PET EXPERIMENTS WITH POSITRON ANNIHILATION*

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Vacuum chambers are necessary for the physics experiments planned to be carried out with the use of the J-PET detector. Two chambers manufactured and used for particular runs of experiments had generally cylindrical shapes, while the radioactive source was placed in the center of each chamber. The highly porous material, used as a target in which positrons/positronium atoms annihilate, was placed in the immediate vicinity of the source. Such orientation ensures the axially symmetrical response of J-PET scintillators and allows to carry out correct calibration. The variation of material used for manufacturing of the chambers (aluminum/plastic), allows to observe the detector response with various rates of absorption and scattering of annihilation quanta. Such determination is necessary for proper analysis of multi-quanta annihilation, which will be needed for planned experiments.

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1. Introduction

Annihilation of positron (first well-known antimatter particle) with electron have found very wide range of applications in medicine and physics. Positron Emission Tomography (PET) is commonly used in tumor diagnosis. In most common version, the glucose marked with ^{18}F radionuclide is applied into patients body immediately before measurement, due to short

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lifetime (158,29(3) min) of given isotope. The marked glucose locates in tissues. Due to annihilation of positron and electron, two antiparallel quanta emitted from patient's body, with the energy of 511 keV each, are collected with the use of tomograph's ring consisted of scintillation detectors equipped with crystal scintillators. Collected data allow the reconstruction of position of altered tissues. It is based on the well-known fact that the metabolism rate of cancerous cells is much higher than normal ones. The difference in the number of registered annihilation events allows to determine the location and size of altered parts of organs.

Much more detailed information from annihilation process is used in material studies. Positron annihilation lifetime spectroscopy (PALS) can be used for determination of electron density/defects in metals and semiconductors [1], size and concentration of free volumes [2] including porosity [3, 4] of investigated materials as well as their chemical activity. Positron applied into investigated sample from radioactive source thermalizes initially due to collisions with surrounding molecules and then, it can annihilate with one of the electrons or create with it (in non-conducting media) a quasi-stable state called positronium. It can occur in two states depending on mutual spin orientation of positron and electron: parapositronium (p-Ps), where spins are antiparallel, and orthopositronium (o-Ps) with parallel spins. These two forms can be distinguished as well as unbound positrons by measuring the time distance between positron emission from radioactive nuclide and positron/positronium annihilation. In a standard approach, positrons are obtained from ^{22}Na radioactive source, in which the γ quantum with energy of 1274 keV is emitted right after positron creation. Registration of such a quantum is used as a "START" signal, while the "STOP" one is taken from registration of annihilation quantum. Then, the respective fractions of positrons/positronium can be determined. During annihilation of electrons with unbound positrons, the 99,7% of events came from 2 quanta annihilation, while the measured lifetimes are in the range of $100 \div 500$ ps. Parapositronium annihilates mainly emitting 2 quanta with the average lifetime of 125 ps. Orthopositronium can annihilate with emission of 3 (intrinsic annihilation) or 2 quanta, due to "pick-off" process [5]. The 3 quanta/2 quanta ratio depends on porosity of investigated material [6] or various effects such as quenching [7, 8], inhibition [9] *etc.* However, the character of annihilation, such as a number of quanta registered during particular, well-known, annihilation processes should be preserved. Violation of this character would testify various symmetry breaking [10–12], which would be one of fundamental aspects in physics research.

The J-PET detector [13–15] is a prototype positron emission tomograph, in which a narrow ring of crystal scintillators was replaced with elongated plastic scintillators surrounding patient's body. The position of hitting the scintillator strip with the quantum is determined from comparison of time response from two photomultipliers placed at its endings. The elongation of the scintillators results in the increase of probability of their crossing with the plain of annihilation. Such a construction may be convenient for both: medical purposes [16–19] and for physics researches [20–25] due to high probability of multi-quanta registration, which could not be obtained with the use of standard narrow tomographs.

2. Basic assumptions and selection of target material

In order to investigate the symmetry violation with J-PET detector, the most important is reaching the highest possible value of the 3 quanta/2 quanta ratio. Therefore, it is necessary to use the highly porous material as a target in which positrons/positronium annihilate and prevent the interaction with scavenger molecules like air, which can reduce the number of registered 3 quanta events by o-Ps quenching. This leads to placing the porous material inside a vacuum chamber. Trial of combining J-PET with positron beam would cause many difficulties due to sizes of both devices. Therefore, using the standard positron source was proposed. In conventional measurements, the mostly used is sandwich orientation, in which a flat positron source is placed between two identical layers of investigated material. The thickness of the target should be chosen to ensure that all positrons/positronium from the source will annihilate inside of it [26], but no additional effects disturbing image reconstruction would be caused. In order to choose a target material, a group of several well-known porous materials *e.g.* polymers/silicas (including porous aerogels) were investigated with the use of porosimetric techniques *i.e.* liquid nitrogen sorption and PALS [27–30]. The 3 quanta/2 quanta ratio was additionally determined with the use of HPGe semiconductor detector and the procedure described in [31]. For experiments, the porous XAD-4 polymer (Amberlite), with the 3 quanta/2 quanta ratio of 24.44(24)% (as received from energy spectra of HPGe detector) was chosen.

Distinguishing 2 and 3 quanta annihilation with the use of scintillation detector with crystal scintillators like BaF₂ is based on determination of the energy of quanta. In 2 quanta annihilation, this energy is 511 keV, while in the case of annihilation with the emission of 3 or more quanta, the total energy of 1022 keV is divided into particular quanta depending on their angular distribution. Therefore, the energy of registered quanta in this case is always lower than 511 keV. However, plastic scintillators used in the J-PET tomograph exclude energy measurement. The only possibility of multi-quanta determination is to register all quanta from each annihilation

event. This requires maximal reduction of annihilation quanta absorption and scattering. Therefore, proposed chambers need to be characterized by thin walls made of material with low atomic number. This excludes the use of steel which results in an inability of use knife-edge seals with copper gaskets. Therefore, the chamber can be sealed only with the use of rubber o-rings, which determines the maximal vacuum level that can be reached at the order of $\sim 10^{-5}$ Pa. Additionally, it should be noticed that whole chamber should be axially symmetrical ensuring uniform response of all scintillators.

3. Technical aspects

Two kinds of materials were taken into account for chamber construction: aluminum and plastic. A series of tests were conducted in order to determine the lowest possible absorption of the quanta emitted during annihilation. The first proposed chamber was prepared from aluminum which combines high mechanical durability with a low Z number. The scheme of the chamber is presented in Fig. 1. The place dedicated for target mate-

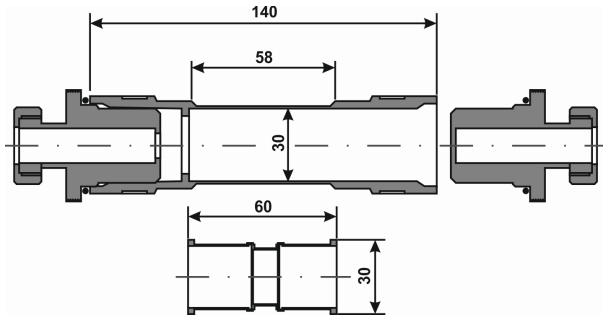


Fig. 1. The scheme of aluminum annihilation chamber (internal “bucket” with the central area for the target material with radioactive source and the external vacuum container) for J-PET experiments.

rial surrounding positron source was located in the center of the internal “bucket”. The thickness of its walls was about 0.4 mm, which was the least that could be manufactured. Slight thickening of the wall in central section determined clearly the positioning of the source. The bucket was placed inside a bigger, external chamber connected to vacuum supply system by steel pipes, which also set the whole chamber in the axis of J-PET detector. The pipes and thick aluminum seals sealed with rubber o-rings were moved away from the central area ensuring that none of the annihilation quanta that can reach the scintillation strips would go through that thickening (Fig. 2). Both, internal and external, chambers reached in the “active” area the maximal total thickness of 1 mm. The absorption of quanta were measured for

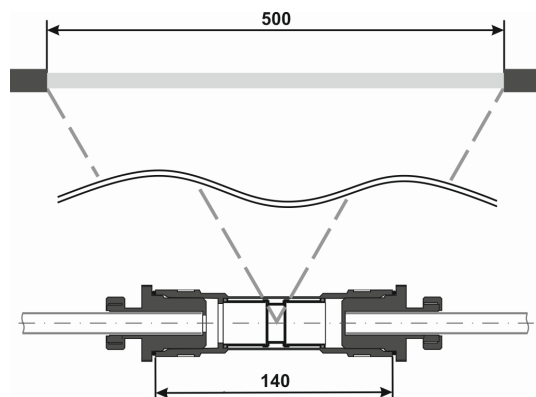


Fig. 2. Mutual position of the annihilation chamber and the strip of the J-PET detector. The dashed lines show the “active” area of the chamber.

this chamber construction by collecting γ and X-ray spectra from ^{152}Eu isotope with HPGe detector with and without the presence of the chamber. Spectra were normalized and then, the relative transmission was calculated for each energy peak. The results presented in Fig. 3 show that even such thin aluminum walls caused quite high absorption of quanta reaching about 50% for the energy less than 50 keV. Such high absorption excludes the usage of aluminum as a chamber material. Further reduction of atomic number of the material dedicated for the chamber was possible by the use of plastics. Therefore, steps were taken in order to check feasibility of such materials. The samples of various plastics with initial thickness of 4 mm were used

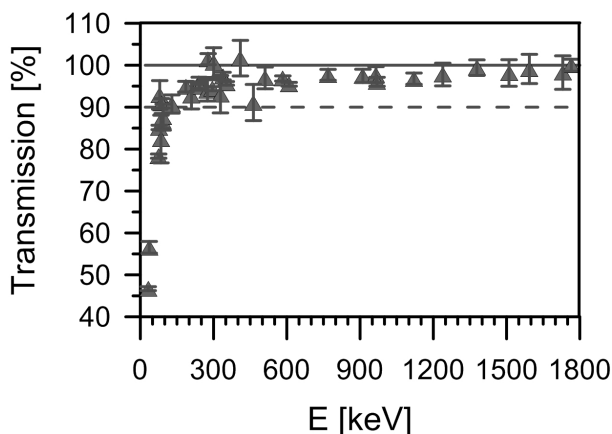


Fig. 3. Transmission of γ quanta from ^{152}Eu isotope through the aluminum chamber dedicated for the J-PET experiments. The dashed line shows the range with the absorption less than 10%.

to test the low absorption material of γ and X-ray quanta from the source consisted of ^{152}Eu and ^{22}Na isotopes. Such a configuration increased the accuracy of the measurements in the low-energy range. The spectra for all the absorbers were normalized to the 511 keV peak, for which no significant absorption was noticed in the measurements for the first chamber. The values of the relative transmission for each of measured energy are shown in Fig. 4(a). It is clearly visible that the absorption of quanta for investigated plastic samples was significantly smaller than for the four times thinner aluminum layer. The highest absorption value for investigated plastic samples reached 24.1(19)% for POM-C at the energy of 168 keV. Such an energy corresponds probably to the backscattering peak for the particular source. The results let to exclude POM-C as a plastic with the highest absorption. From the rest of materials, the PA6 plastic was chosen due to high durability and ease of processing. The results for the transmission tests, in the same configuration as previously, with PA6 samples of various thickness are presented in Fig. 4(b). It was shown that reduction of material thickness

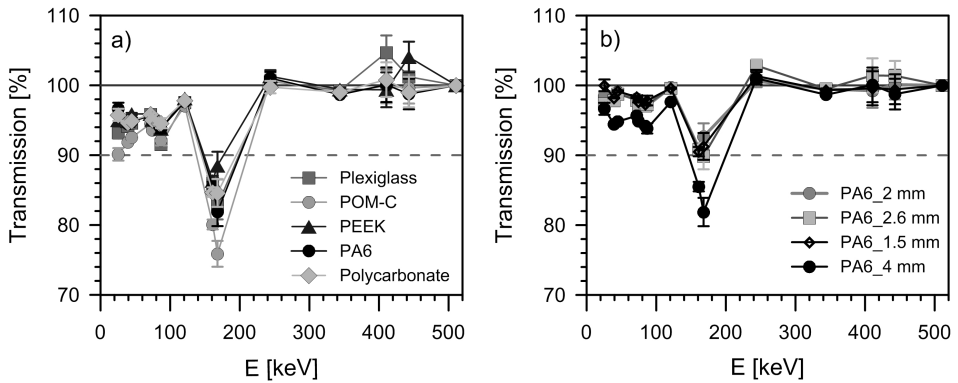


Fig. 4. Transmission of γ and X-ray quanta for: (a) various plastic materials, (b) PA6 plastic with various thickness. The investigated spectra were normalized to the 511 keV energy peak.

even to 2.6 mm caused the decrease of absorption value below 10% which is significant improvement compared with the aluminum chamber. Additionally, the average absorption is lower than 5% even in the low-energy range. The scheme of the second chamber, manufactured with the use of PA6 plastic, is presented in Fig. 5. The thickness of the sample layer was the same as previously, while the thickness of chamber walls in the active range of the detector was 0.6 mm. After filling the internal area with the sample surrounding the source, the plastic partition was placed to close the sample area. The thickness of the partition and the chamber walls were chosen to ensure uniform thickness of the chamber in the whole active range. Despite

the small thickness of the walls, the chamber had been successfully attached to the vacuum supply system and the air had been pumped out from the chamber with the use of turbomolecular pump without any damages of the chamber.

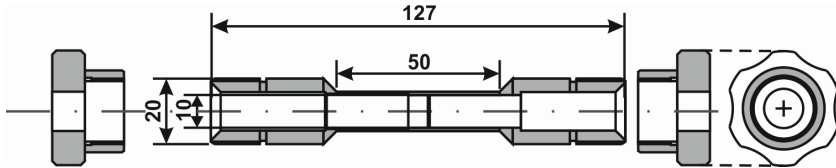


Fig. 5. The scheme of PA6 annihilation chamber for J-PET experiments.

4. Conclusions

Two vacuum chambers suitable for the J-PET detector were manufactured and tested. Localization of the target sample in the vicinity of the positron source was necessary to obtain symmetrical response of the tomography which allowed proper calibration. It was shown that the use of aluminum as a material for the chamber was improper due to high absorption of annihilation quanta which would disturb the multi-quanta reconstruction. The plastic chamber with low absorption rate was manufactured in order to improve the number of registered quanta from multi-quanta events. The annihilation experiments with the use of these chambers were necessary for a proper calibration of J-PET detector and improvement of its parameters. This is important due to plans of conducting the measurements with testing discrete symmetries in physics.

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REFERENCES

- [1] R. Krause-Rehberg, H.S. Leipner, *Positrons in Semiconductors*, Springer-Verlag Berlin Heidelberg, 1999.
- [2] M. Eldrup, D. Lightbody, J.N. Sherwood, *Chem. Phys.* **63**, 51 (1981).
- [3] T. Goworek *et al.*, *Chem. Phys.* **230**, 305 (1998).
- [4] R. Zaleski, *Nukleonika* **60**, 795 (2015).
- [5] R.L. Garwin, *Phys. Rev.* **91**, 1571 (1953).

- [6] A.P. Mills Jr., *Phys. Rev. Lett.* **41**, 1828 (1978).
- [7] S.Y. Chuang, S.J. Tao, *Appl. Phys.* **3**, 199 (1974).
- [8] G. Duplatre, I. Billard, *Principles and Applications of Positron and Positronium Chemistry*, (Eds.) Y.C. Jean, P.E. Mallon, D.M. Schrader, World Scientific, 2003, DOI:10.1142/9789812775610_0001.
- [9] K. Hirata *et al.*, *J. Chem. Soc., Faraday Trans.* **93**, 139 (1997).
- [10] W. Bernreuther *et al.*, *Z. Phys. C* **41**, 143 (1988).
- [11] B.K. Arbic *et al.*, *Phys. Rev. A* **37**, 3189 (1988).
- [12] S. Bass, *Acta Phys. Pol. B* **50**, 1319 (2019).
- [13] P. Moskal *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **764**, 317 (2014).
- [14] P. Moskal *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **775**, 54 (2015).
- [15] P. Moskal *et al.*, *Phys. Med. Biol.* **61**, 2025 (2016).
- [16] S. Niedźwiecki *et al.*, *Acta Phys. Pol. B* **48**, 1567 (2017).
- [17] P. Moskal *et al.*, *Phys. Med. Biol.* **64**, 055017 (2019).
- [18] P. Moskal, B. Jasińska, E.Ł. Stępień, S. Bass, *Nature Rev. Phys.* **1**, 527 (2019).
- [19] P. Kowalski *et al.*, *Phys. Med. Biol.* **63**, 165008 (2018).
- [20] D. Kamińska *et al.*, *Nukleonika* **60**, 729 (2015).
- [21] P. Moskal *et al.*, *Acta Phys. Pol. B* **47**, 509 (2016).
- [22] J. Raj *et al.*, *Hyperfine Interact.* **239**, 56 (2018).
- [23] P. Moskal *et al.*, *Eur. Phys. J. C* **78**, 970 (2018).
- [24] B. Hiesmayr, P. Moskal, *Sci. Rep.* **7**, 15349 (2017).
- [25] B. Hiesmayr, P. Moskal, *Sci. Rep.* **9**, 8166 (2019).
- [26] J. Dryzek, *Acta Phys. Pol. A* **107**, 598 (2005).
- [27] J. Wawryszczuk *et al.*, *Langmuir* **19**, 2599 (2003).
- [28] R. Zaleski *et al.*, *J. Colloid Interface Sci.* **358**, 268 (2011).
- [29] M. Gorgol *et al.*, *MICMAT* **163**, 276 (2012).
- [30] R. Reisfeld *et al.*, *J. Lumin.* **169**, 440 (2016).
- [31] B. Jasińska *et al.*, *Acta Phys. Pol. B* **47**, 453 (2016).