

RESEARCH

Estimating relationship between the Time Over Threshold and energy loss by photons in plastic scintillators used in the J-PET scanner

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Abstract

Purpose: Time-Over-Threshold (TOT) technique is being used widely due to its implications in developing the multi-channel readouts mainly when fast signal processing is required. Using TOT technique as a measure of energy loss instead of charge integration methods significantly reduces the signals readout cost by combining the time and energy information. Therefore, this approach can potentially be used in J-PET tomograph which is build from plastic scintillators characterized by fast light signals. The drawback in adopting this technique is lying in the non-linear correlation between input energy loss and TOT of the signal. The main motivation behind this work is to develop the relationship between TOT and energy loss and validate it with the J-PET tomograph.

Methods: The experiment was performed using the ²²Na beta emitter source placed in the center of the J-PET tomograph. One can obtain primary photons of two different energies: 511 keV photon from the annihilation of positron (direct annihilation or through the formation of para-Positronium atom or pick-off process of ortho-Positronium atoms), and 1275 keV prompt photon. This allows to study the correlation between TOT values and energy loss for energy range up to 1000 keV. As the photon interacts dominantly via Compton scattering inside the plastic scintillator, there is no direct information of primary photon's energy. However, using the J-PET geometry one can measure the scattering angle of the interacting photon. Since, ²²Na source emits photons of two different energies, it is required to know unambiguously the energy of incident photons and its corresponding scattering angle for the estimation of energy deposition. In this work, dedicated algorithms were developed to tag the photons of different energies and studying their scattering angles to calculate the energy deposition by the interacting photons.

Results: A new method was elaborated to measure the energy loss by interacting photons with plastic scintillators used in J-PET tomograph. It is found that relationship between the energy loss and Time Over Threshold is non-linear and can be described by function $TOT = A0 + A1 * \ln(E_{dep} + A2) + A3 * (\ln(E_{dep} + A2))^2$.

Conclusions: A relationship between Time Over Threshold and energy loss by interacting photons inside the plastic scintillators used in J-PET scanner is established for a energy deposited range 100-1000 keV.

Keywords: positron emission tomography; Time Over Threshold; Positronium atoms; medical imaging

1 Background

Time-Over-Threshold (TOT) technique was introduced first time by Nygren and Millaud¹ and proved to be an excellent solution for the multi-channel readouts². In the TOT method, one basically measures the signal pulse width at the selected thresholds, which can be used as the estimate of the signal's charge. For the energy deposition estimation this method is less precise in comparison to charge integration method. However, it reduces the readout cost by using only time to digital converter (TDC) combining both timing and energy information. Application of TOT method for the energy loss determination may be of particular advantage in the newly developed J-PET positron emission tomograph^{3,4} which is based on plastic scintillators characterized by fast light signals with rise and decay times of the order of ≈ 1 ns^{5,6} and thus being about two orders of magnitude shorter than signals from crystals used in the current PET devices⁷⁻⁹. Therefore, application of the TOT method in case of the J-PET tomograph build from plastic scintillators will enable fast signal processing reducing significantly signal acquisition dead time with respect to the crystal based tomographs. Despite of advantages providing the compactness of signals readout and low power consumption, the TOT technique confronts the challenge in terms of non-linear input energy to pulse width conversion¹⁰⁻¹². It has been reported that using the multiple fixed triggering thresholds^{13,14} or dynamic threshold levels^{15,16} for estimating the TOT values alleviate the problem of non-linearity to significant extent.

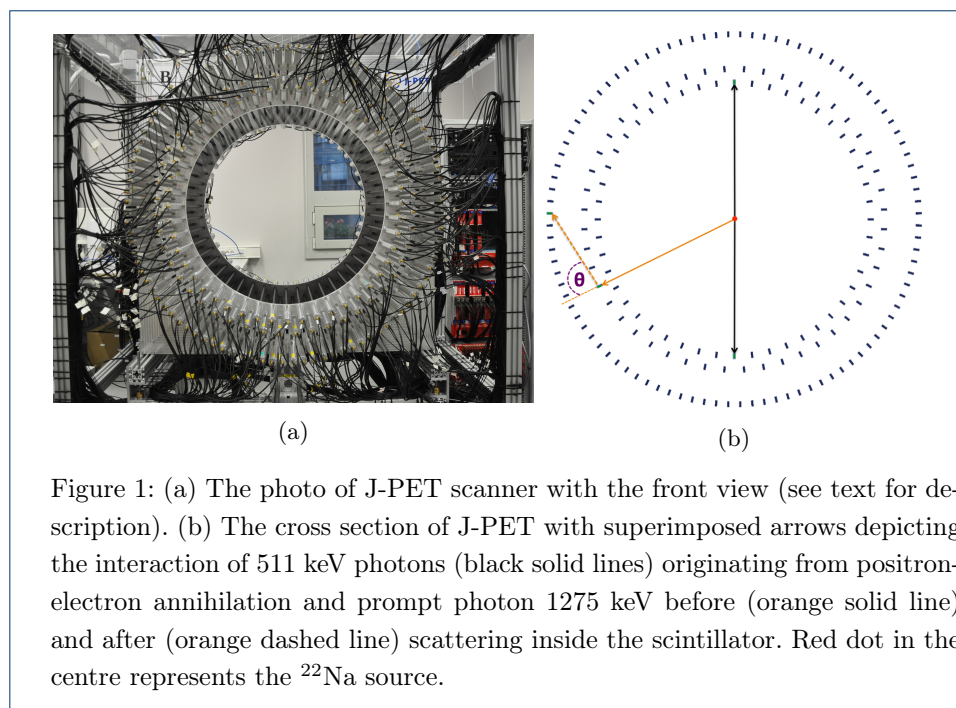
In Positron Emission Tomograph (PET) applications, the precise determination of the photon's interaction position, hit time and energy loss is crucial. Currently in PET scanners, crystal scintillators are used and they enable to determine energy of interacting photons as they undergo photoelectric effect^{17,18}. But in plastic scintillators the incident photon interacts via Compton scattering depositing only part of its energy. So, there is no direct information of energy deposition of the interacting photon.

TOT studies with the plastic scintillators are very scarce¹⁹. In the recent work of Ashrafi and Gol²⁰, energy calibration of a plastic scintillator based on the Compton scattering and observing the light yield by using various monochromatic photon source was reported. In this work we take advantage of the multilayer cylindrical acceptance of the J-PET scanner^{3,21} which allows to determine the direction of photon before and after the scattering and by that gives access to its scattering angle^{4,22}. Thus, knowing the incident energy and the measured scattering angle of initial photon, the deposited energy in the photon's interaction can be calculated²³. For the present study, ²²Na source was used which emits photons of two different energies 511 keV (annihilation) and 1275 keV (prompt). The 511 keV photons are originating from the direct electron-positron annihilation, from the decay of para-positronium and from annihilation of ortho-positronium atoms via the pick-off processes²⁴⁻²⁶. Since the aim of the study is to establish the relationship between TOT and energy loss it is required to develop an algorithm to clearly distinguish between the annihilation and prompt photons emitted from the source as well as a method of the proper association of measured signals to initial and scattered photons. To achieve this, we performed studies bases on the assumptions that 511 keV photons emitted in the annihilation of e^+e^- are always back-to-back due to the momentum

conservation. Secondly, to identify the prompt photons, we take advantage of the decay of long-lived ortho-positronium atoms²⁷ which in the XAD-4 porous polymer²⁸ on the average decay in about 90 ns after the emission of a prompt photon. In this article we present a method for establishing a relationship between TOT and the energy deposition.

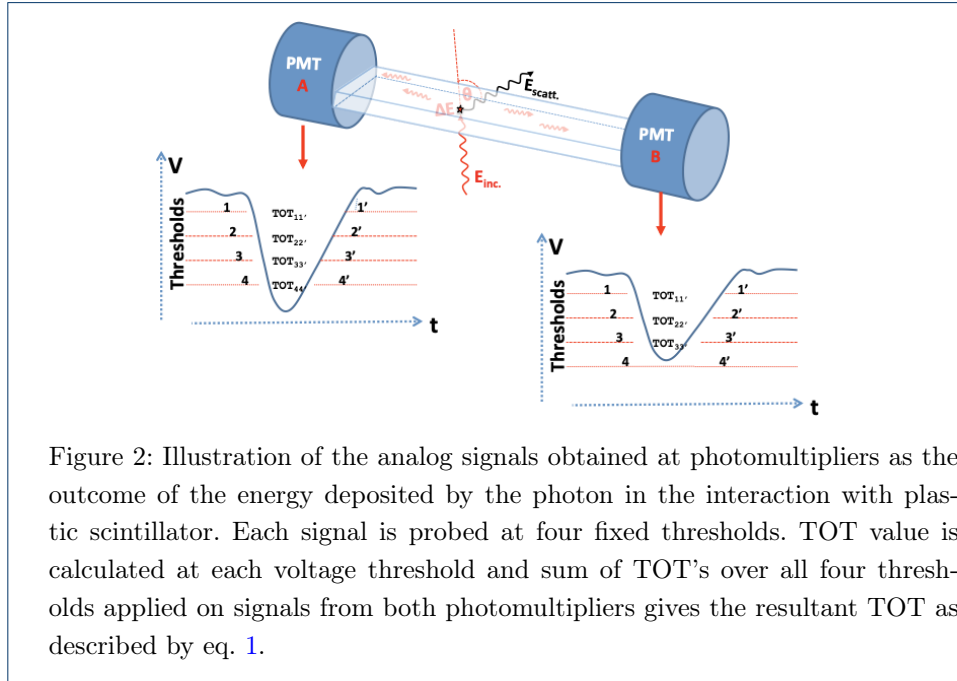
2 Methods

The Jagiellonian - Positron Emission Tomograph (J-PET) is constructed of 192 plastic scintillators made of EJ-230 material. Scintillator with dimension $0.7 \times 1.9 \times 50 \text{ cm}^3$ connected with R9800 Hamamatsu photomultiplier on each side composes a single detection module^{29,30}. The detection modules are axially arranged in three layers: the first and second layers are composed of 48 modules whereas the third layer is the arrangement of 96 modules. Layers are not overlaying each other and are of diameters 85 cm, 93.5 cm and 115 cm respectively. The front view of three layer prototype of the J-PET scanner is shown in Fig. 1a whereas Fig. 1b exhibits its cross section. A Multi-Voltage Threshold mezzanine (MVT) board is used to probe signals at four fixed thresholds (80, 160, 240 and 320 mV) in voltage domain (within the accuracy of 20 ps RMS)³¹ to achieve the good resolution of determining the hit time and place of interaction of photon inside the scintillator^{3,30,32-34}. Using



MVT boards, connected to readouts allow to exploit the FPGAs differential inputs as comparators. The signals from MVT boards are sampled using TDC implemented in the FPGA devices³⁵⁻³⁸ whereas in standard approach external comparator chips are used additionally^{39,40}. The data is stored in trigger less mode with an ability to handle the data stream with rates of about 8 Gbps^{41,42}. The position of interaction along the plastic strip is calculated based on the time difference of light signals arriving at both photomultipliers. Signals from the plastic scintillators are very

fast (rise time ≈ 0.5 ns, fall time ≈ 1.8 ns)⁶ and are prone to much lower pile-ups with respect to crystal based detectors with order of magnitude larger fall times⁴³. Therefore, to avoid the dead time due to the direct charge measurement, only timing of signals is used. The photon's interaction in scintillator and the arrival time of the signals in photomultipliers at each end is measured. TOT approach is adopted instead of charge integration method. In TOT approach, the time difference between the leading and trailing edge of signal pulse crossing the applied thresholds is measured. The schematic presentation is shown in Fig. 2. The total TOT, used as



a measure of the energy deposition, is estimated as a sum of TOT values measured for all thresholds at both sides of scintillator (eq. 1):

$$TOT = \sum_{PMT=A,B} \sum_{Thr_{1-4}} TOT_{PMT,Thr} \quad (1)$$

Besides attractive features in terms of significant reduction in the cost of signal read out, low electricity consumption (2.76 W per channel) and high flux rate handling, the estimation of the charge collection using the pulse width of the signal is less precise and suffers a strongly non-linear relationship between TOT and energy deposition. The plastic scintillators are composed of hydrocarbons with low atomic (Z) number, consequently the gamma photons interact in plastic scintillators predominantly through the Compton scattering and deposit only part of their energy. The information of the deposited energy is important to reduce the scatter fraction by requiring the energy loss larger than 200 keV^{3,22,33}. To process the measured data a dedicated framework for the offline data analysis was used^{44,45}.

2.1 Experimental set-up

The measurements were performed with a ^{22}Na source (1 MBq activity) wrapped inside a very thin kapton foil. The experimental set-up is shown in Fig. 3. Left panel shows picture of the J-PET tomograph with the placement of a barrel shape source holder of length ≈ 14 cm and diameter ~ 3.16 cm (at the center). The source surrounded by the porous material was put inside a small chamber of thin layer made of aluminium and placed at the center of holder (see upper inset of right panel in Fig. 3). The placement of the source covered with porous material is shown at lower right insets. In this experiment, the XAD-4 polymer was used which increases the probability of formation of Ps atoms²⁸. Using the ^{22}Na source gives

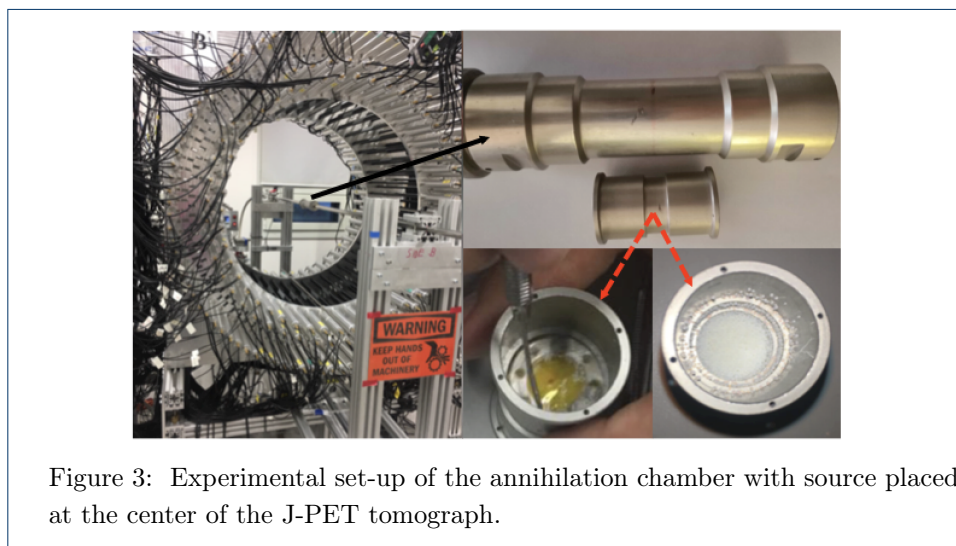


Figure 3: Experimental set-up of the annihilation chamber with source placed at the center of the J-PET tomograph.

a possibility to estimate the lifetime of the Ps atom by registering the annihilation photons and prompt gamma. In the decay of ^{22}Na source (Fig. 4a), the positron is

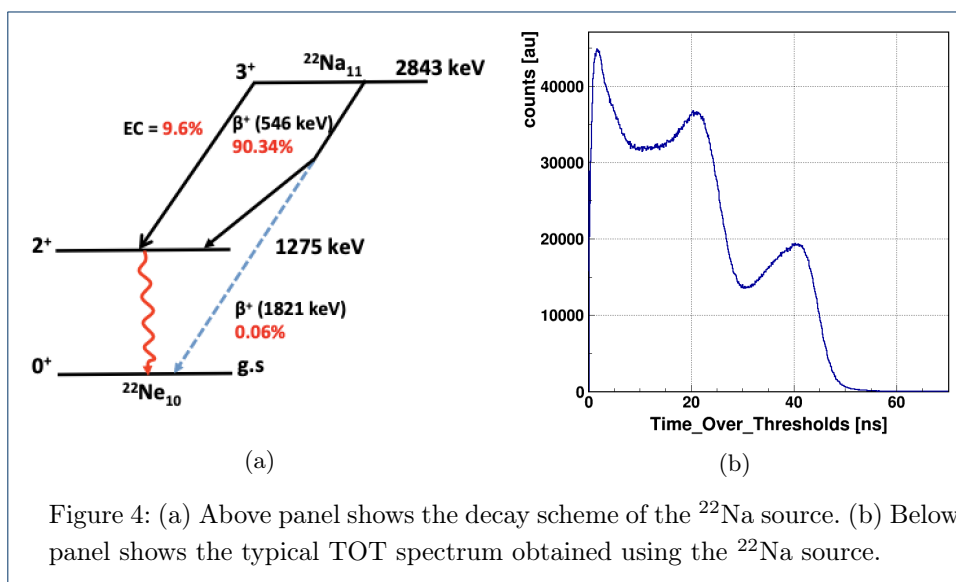
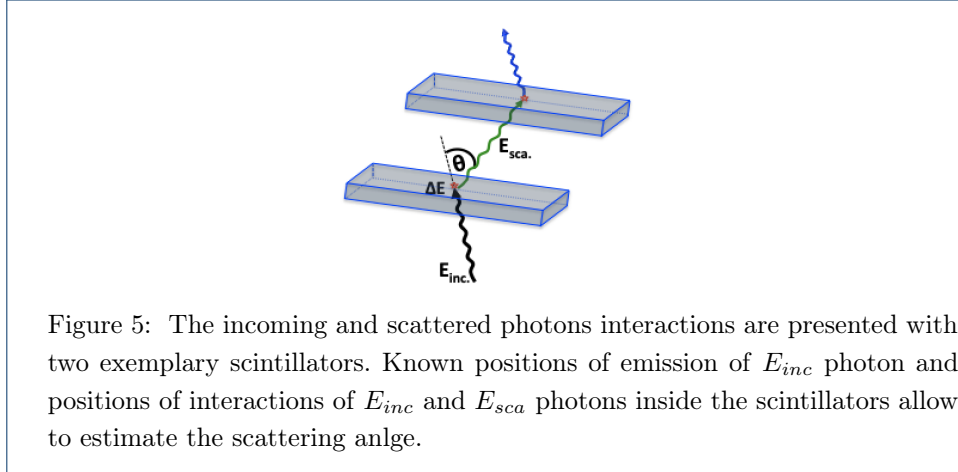


Figure 4: (a) Above panel shows the decay scheme of the ^{22}Na source. (b) Below panel shows the typical TOT spectrum obtained using the ^{22}Na source.

emitted leaving behind an excited state of ^{22}Ne nucleus which de-excite eventually

via emission of prompt photon on average within the time interval of ≈ 3.7 ps. The time difference between the interaction of annihilation and prompt photons is then with a very good approximation equal to lifetime of Ps atom²⁵. Gamma photons mainly interact inside the plastic scintillator via Compton scattering.

Fig. 4b shows the TOT spectrum for all registered photons. The clear Compton edges are visible at about 22 ns and 46 ns corresponding to 511 keV and 1275 keV photons respectively. The enhancement of contribution for the lower values of TOT (below 10 ns) is from the interaction of scattered photon and photons originating from the 3-photon decay of o-Ps atoms. It is worth to emphasize that TOT values could be used to disentangle between the annihilation and prompt photons to some extent. However, in the overlapping region for TOT values below 30 ns the identification would not be unambiguous. Therefore, we developed a dedicated algorithm to uniquely identify the photons of energies 511 keV and 1275 keV irrespective of TOT values (described in sec. 2.2). Furthermore, the registration of initial and



scattered photons allows to determine the scattering angle θ (see Fig. 5). Known energy (E_{inc}) and scattering angle (θ) of the initial photon give access to energy deposition ΔE inside the scintillator²³:

$$\Delta E = E_{inc} \left[1 - \frac{1}{1 + \frac{E_{inc}}{511} (1 - \cos\theta)} \right] \quad (2)$$

Determination of ΔE and the measurement of TOT enables to establish the relation between these two variables.

In this work, events with three interactions were studied, assuring that all three hits forming the events are occurring in distinct scintillators. Furthermore, a photon interaction inside the scintillator is termed as hit. The required information (E_{inc}, θ) can be extracted based on two hits only. However, the third hit allows the event categorization in a way that we can differentiate the photons of different energies and conjecture their origins.

2.2 Events selection

In this analysis, we first select the events with three hits only. The angular correlations between the registered photons in three hit events can be used partially to identify the origin and energy of photons^{46,47}. The pictorial view of the three

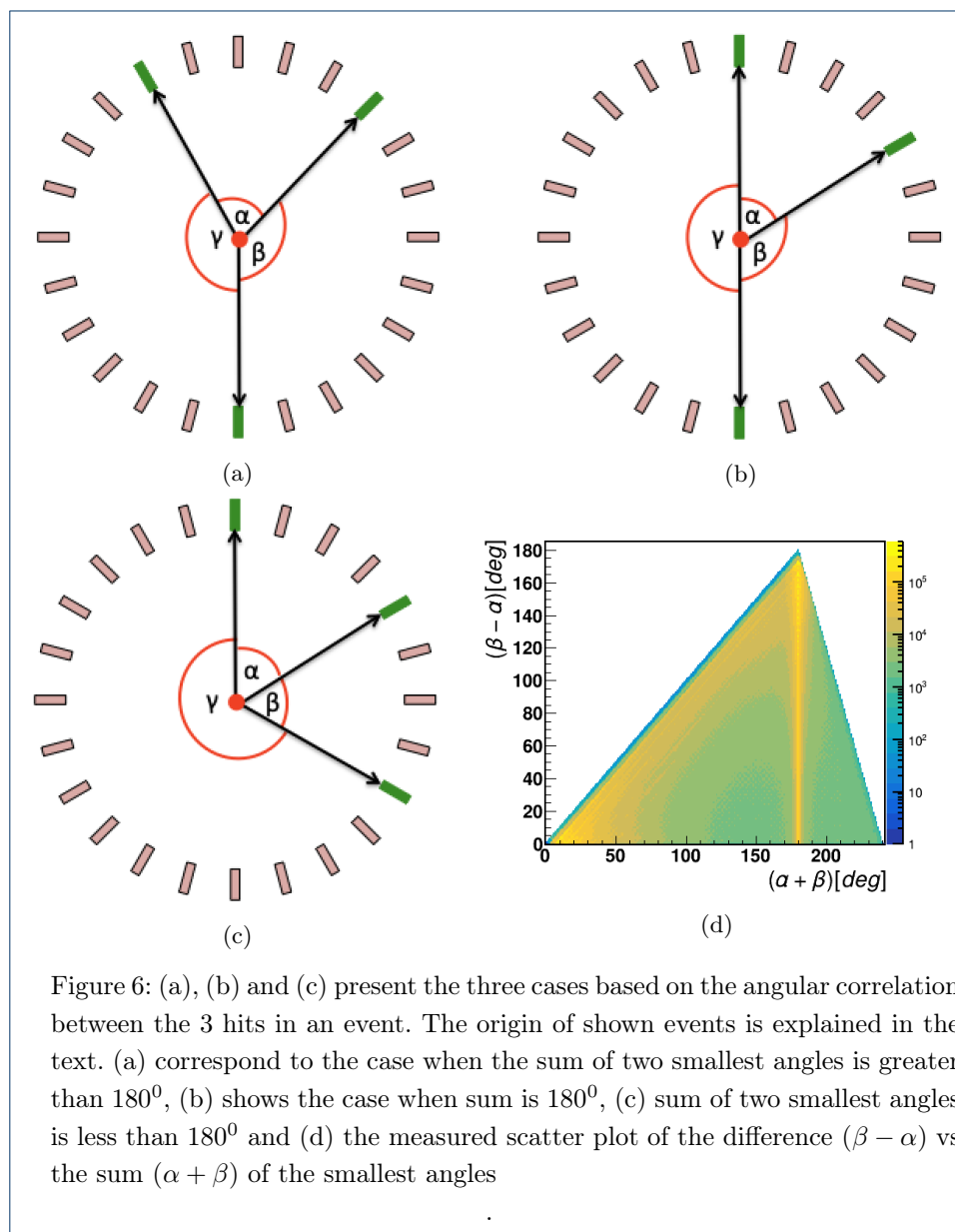


Figure 6: (a), (b) and (c) present the three cases based on the angular correlation between the 3 hits in an event. The origin of shown events is explained in the text. (a) correspond to the case when the sum of two smallest angles is greater than 180° , (b) shows the case when sum is 180° , (c) sum of two smallest angles is less than 180° and (d) the measured scatter plot of the difference $(\beta - \alpha)$ vs the sum $(\alpha + \beta)$ of the smallest angles

hits (green rectangles) and their angular correlations are presented in Fig. 6a - 6c. For the clarity, only few scintillators mimicking the one layer of J-PET scanner are shown. The angles between three hits ordered from the smallest to the largest are α , β and γ respectively. A measured sum of the two smallest angles vs their difference is shown in Fig. 6d which shows three distinct regions: (i) $(\alpha + \beta) > 180$ degree, electron-positron annihilation into three photons originating from direct e^+e^- annihilation or from the decay of o-Ps atoms (ii) $(\alpha + \beta) = 180$, two back-to-back photons originating either from direct e^+e^- annihilation or from the decay of p-Ps

atom (Singlet state of Ps) or from the pick-off of o-Ps (iii) $(\alpha+\beta) < 180$, one or two of the hits are from scattering of initial photon or prompt photon.

2.3 Identification of 511 keV photons

The 511 keV photons are the outcome of e^+e^- annihilation into back-to-back direction to preserve the momentum conservation and can easily be identified in Fig. 6d as a vertical line at $\alpha+\beta=180^\circ$. The selection of such events was done based on the condition that the sum of the two smallest angles $(\alpha+\beta)$ should be 180° within the uncertainty of two degrees. The pictorial presentation of J-PET with one layer is used to visualize the situation. In Fig. 7a, black lines represent the back-to-back photons labeled as 1 and 2 and orange line shows the prompt photon. Scintillators

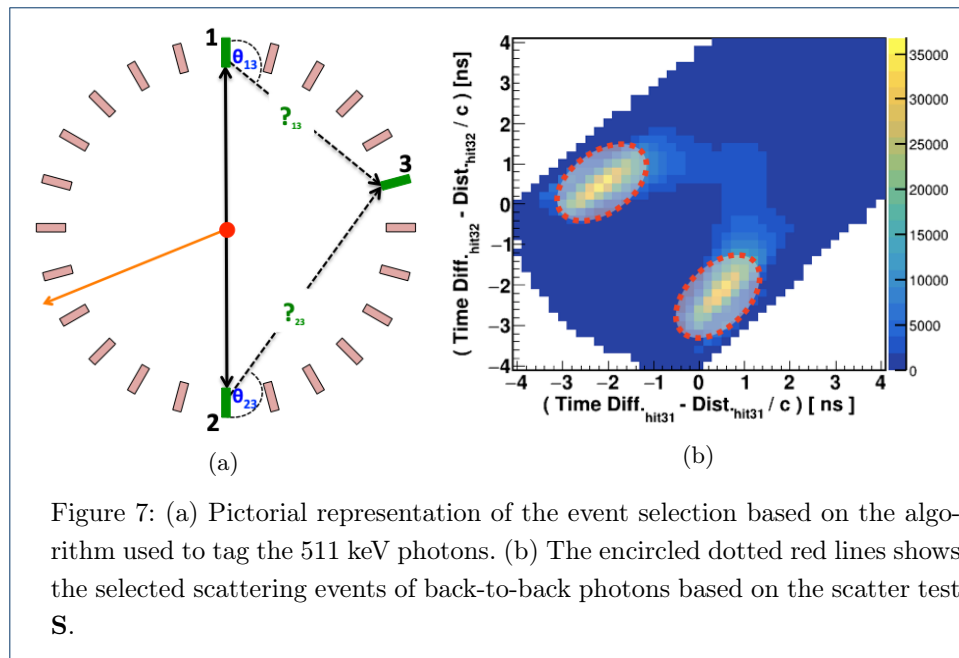


Figure 7: (a) Pictorial representation of the event selection based on the algorithm used to tag the 511 keV photons. (b) The encircled dotted red lines shows the selected scattering events of back-to-back photons based on the scatter test S .

with photons hits are shown as green rectangles. Hit 3 corresponds to the interaction of the scattered photon after Hit 1 or Hit 2. The exact assignment of scattering photons to its primary one is important for the proper estimation of scattering angle (Fig. 7b) which is essential for exact energy deposition. For this purpose, a scatter test S is devised which estimates the time difference between the measured time (time difference between two hits) and calculated time (distance between hit-positions divided by the speed of light). The S -test was applied event-wise assuming both possibility that the third hit might belong to the scattering photon after Hit 1 or Hit 2. The results are shown in Fig. 7b. In case of the proper assignment the value of S should be close to zero. For the final analysis, events from the areas encircled by red-dotted lines were taken into account.

With the known incident photon's energy (511 keV) and its scattering angle, the deposited energy is calculated in response to the initial hit. Thus, a one-to-one information of energy deposition by 511 keV photons and corresponding TOT values on event-wise bases is extracted. In studying 511 keV photons the relationship can be established only upto 340 keV energy deposition (Compton edge for 511 keV photon). So, In order to extend the relationship for higher energy deposition values, the studies with the prompt photons with energy 1275 keV are also performed. The selection criterion for the prompt gamma is explained in the next sub-section.

2.4 Identification of 1275 keV photons and their scatterings

The selection of prompt and its corresponding scatter photon without using the explicit cut on TOT values is not as straight forward as in the case of annihilation photons. As the first step in the selection procedure, in order to suppress events

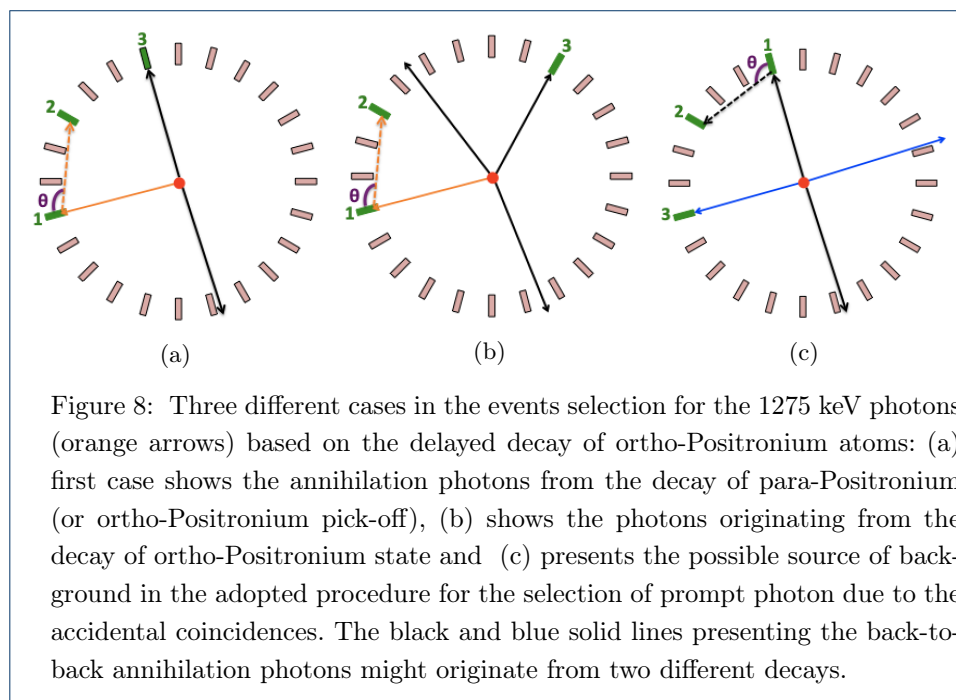
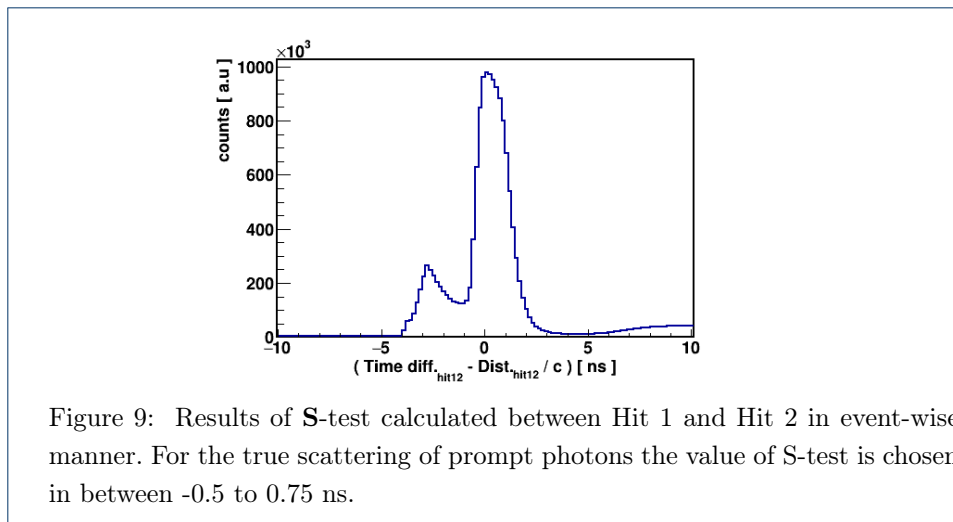


Figure 8: Three different cases in the events selection for the 1275 keV photons (orange arrows) based on the delayed decay of ortho-Positronium atoms: (a) first case shows the annihilation photons from the decay of para-Positronium (or ortho-Positronium pick-off), (b) shows the photons originating from the decay of ortho-Positronium state and (c) presents the possible source of background in the adopted procedure for the selection of prompt photon due to the accidental coincidences. The black and blue solid lines presenting the back-to-back annihilation photons might originate from two different decays.

with back-to-back 511 photons, we applied the cut based on the angular correlation between the hits (Fig. 6d) such that we are not considering those events when the sum of two smallest angles lie in interval $165^{\circ} - 185^{\circ}$ degrees. In the next step, hits are ordered according to the ascending time and only those events are selected for which time interval between first and third hit is larger than 10 ns. The assumed analogy is as follows: Hit 1 is considered to be the prompt photon, Hit 2 is the scattered photon of the prompt, and Hit 3 is assumed by one of the photons originating from pick-off (Fig. 8a) or direct from the decay of ortho-positronium atoms (Fig. 8b) Fig. 8c shows the possible background in the adopted selection criterion. The time difference (Δt) between the first and third hit is used as a key parameter. It is chosen to be much larger than the possible time difference between the scatterings of photon in the tomograph. For the present analysis, the value for Δt was fixed in time interval (10 ns - 100 ns). For estimating the scattering angles

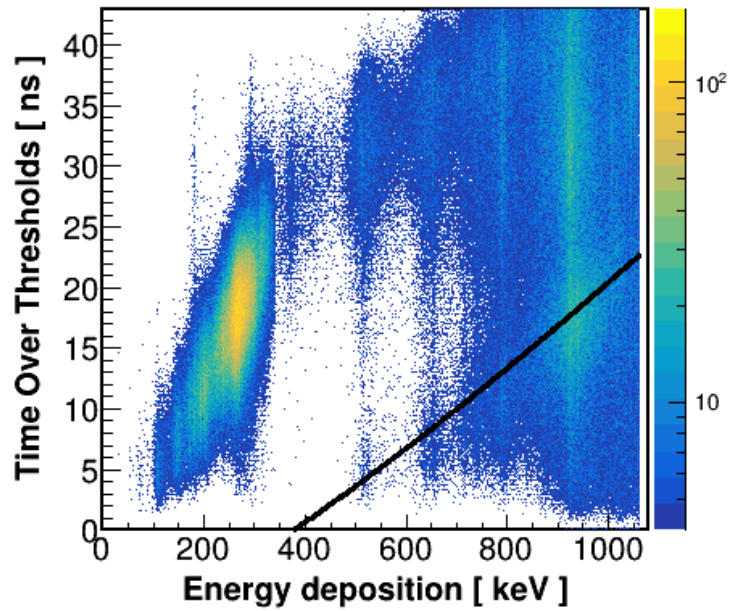


of prompt gamma, the scattered test was applied between first and second hit. The histogram used for the scatter test is shown in Fig. 9. The acceptance time window for the true scattering of the **S**-test is chosen between -0.5 to 0.75 ns.

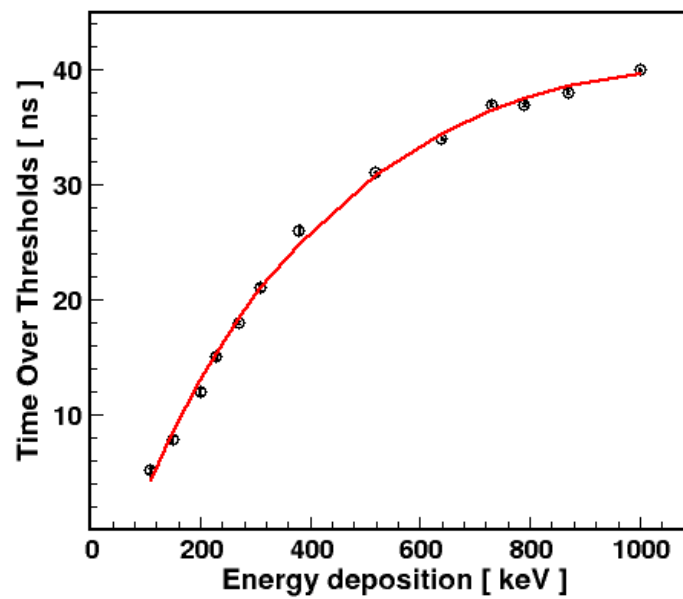
3 Results

The motivation of this work is the elaboration of a method to estimate the energy loss by incident photons in the interaction with plastic scintillators used in J-PET tomography scanner. The analysis is performed with the ^{22}Na isotope because it is long lived (2.6 years half lifetime) and is emitting positrons annihilating to 511 keV photons as used in the PET diagnostics. Since, the aim of this study is to establish the relation between TOT and ΔE for the plastic scintillators, in order to avoid the biasness in identification of 511 keV (positron annihilation) and 1275 keV (de-excitation) photons, a new method of photon identification was developed which is independent of the TOT values. After selecting the photons of different energies, their scattering angles are estimated based on the hit characteristics. With the information of incident energy of photon and its scattering direction, the energy transfer to the electrons inside the scintillator can be calculated using the Compton scattering formula (eq. 2).

In each event, hit characteristics are measured that comprise the TOT values, photon's interaction time as well as spatial coordinates. For all selected hits, the relationship between measured TOT values and the estimated energy deposition is presented in Fig. 10a. An enhancement in TOT values is observed with increasing energy depositions which is an expected behavior. However, some contribution is visible with large energy deposition but less TOT values, which can be interpreted as the wrongly tagged photon due to the accidental coincidences i.e., instead of 1275 keV photon, photons with lower incident energies were used to estimate the energy deposition for the scattering angles.(e.g., see the Fig. 8c). The black line in 10a is plotted by assuming that the wrongly tagged photons are of energy 511 keV. For the final relationship, the profile histograms of Fig. 10a for the most populated energy bins are selected. The mean values of the TOT distributions as a function of the center value of the energy interval is shown in Fig. 10b. The black circles are



(a)



(b)

Figure 10: (a) 2-D spectrum of TOT versus energy deposition. (b) TOT vs energy deposition. Red line indicates result of the fit of the function: $TOT = A0 + A1 * \ln(E_{dep} + A2) + A3 * (\ln(E_{dep} + A2))^2$, with $A0 = -2332$ ns, $A1 = 632.1$ ns/keV, $A2 = 606.9$ keV and $A3 = -42.08$ ns/(keV)².

the experimental data. Errors in estimating the mean value of the TOT are within the size of the used symbols. It is shown that a simple function (see the caption of Fig. 10) is able to reproduce the data for quite a large range of energy deposition, i.e. up to 950 keV.

4 Conclusions

The J-PET is first PET scanner composed of plastic scintillators^{3,29}. Plastic scintillators are more than an order of magnitude less expensive than the crystal scintillators. Time-Over-Threshold approach facilitates a compact, fast and cost effective signal readout^{31,41,42}. In the framework of J-PET scanner, TOT approach is adopted as the measure of the energy deposition to utilize the fast timing and low pile-up features of the plastics scintillators. To use this method effectively in comparison to the classical method of charge collection, it is important to know the non-linear relationship between the energy deposition of an initial photon and the measured TOT values. Here, we presented a method for determining relation between the energy deposition and TOT which can be efficiently applied to the J-PET tomograph by collecting the data with the ²²Na source covered with the porous material characterized with the long lifetime of positronium atoms²⁸. The identification of an incident photon was based on angular correlation between the three hits and the lifetime of the metastable positronium atoms while the scattered photon was identified and associated to the initial photon based on the correlation among the time and distance between the interaction points. Using ²²Na source emitting 1275 keV prompt and 511 keV annihilation photons, the TOT versus energy loss relationship up to about 1000 keV was established. The proposed function fits well the experimental data and can be used as a standalone function for the energy loss calibration of the plastic scintillators used in the J-PET scanner.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon request.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

All authors contributed in the elaboration of methods for data analysis, interpretation of results, experimental set-up and data collection, correction of manuscript and approval. The analysis algorithm was mainly developed by SS along with the PM. SS and PM edited the manuscript.

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