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Optimization of a multi-ring detector for Ps time of flight measurements

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Abstract. We have designed a multi-ring detector (MRD) based on Bismuth Germanate (BGO) crystals, coupled to Silicon PhotoMultipliers (SiPM) for measuring the Ps time of flight (TOF). The set-up geometry was optimized by Monte Carlo simulations to take into account at different Ps velocities: (i) the background noise due to backscattered positrons, (ii) the cross-talk between adjacent detectors, (iii) the lifetime of Ps decay. Three parameters were defined to evaluate the different configurations and a figure of merit was obtained. This allows the choice of the best set up configuration for measuring Ps emitted with a particular energy range, optimizing the signal to noise ratio and keeping the acquisition time acceptable.

1. Introduction

A TOF apparatus to investigate Ps cooling by measuring the energy distribution of Ps emitted from porous materials was developed in Trento [1] and it is being set up at the NEutron induced POsitron Source MUnich (NEPOMUC) [2]. The system was realized to work with continuous e^+ beams. The secondary electrons ejected by the e^+ entering the sample are used as start signal as recorded by two channeltrons. The stop signal is given by the Ps annihilation γ rays observed by detectors placed at a known distance z from the sample surface. In order to improve the efficiency of this apparatus we designed a 4-ring detector where each ring is separated from another ring by tungsten shields. A multi-ring detector MRD allows the acquisition of simultaneously TOF spectra at different distances. Since the MRD requires small size detectors, BGO crystals, with 4x4x10 mm^3 dimensions, coupled with SiPMs were considered [3].

2. Monte Carlo Simulations and results

To take into account the increasing of the noise caused by background signal from the backscattered positrons and by false counts of Ps that don't annihilate in front of the ring (*cross-talk effect* between adjacent detectors), many Monte Carlo simulations have been carried for different configurations obtained varying the thickness ($t \div$1-9 mm) of the shield among the detector's rings together with the

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distance (d÷20-90 mm) between the detectors and the chamber axis (see figure 1). Each ring covers an angle of 180° in the xy plane and the slit dimension was chosen to be Δ=4 mm to fit with the BGO-SiPMs dimensions. The distance h between the target and the middle of the first ring was fixed to 1 cm, while D=10 mm was the radius of the chamber [3]. To extract a figure of merit, three parameters $M1_j$, $M2_j$, $M3_j$ were defined for each ring j, and studied at different velocities v of the emitted Ps:

- $M1_j$ is the fraction of Ps detected by each ring j and $M1 = \sum_{j=1}^{4} M1_j$;
- $M2_j$ takes into account the rate of the noise events due to the background γ rays coming from e^+ annihilation on the chamber walls and detected in each ring *j;*
- $M3_j$ takes into account the rate of the false events due to the *cross-talk* recorded in each ring *j*.

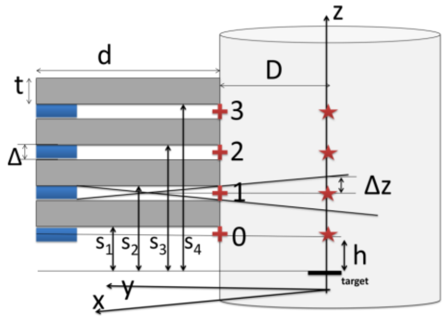

Figure 1. Geometry of the set up used in the Monte Carlo simulations

By considering Ps annihilating in flight along the z axis (stars in figure 1), the $M1_j$ parameters can be calculated as the product of the solid angle $\alpha_j(d) = \frac{\pi\Delta}{d+D}$ and the probability that Ps decays in front of each detector j. Defining the lower z-coordinate of each ring $s_i = h + \frac{\Delta}{2} + i\,(t + \Delta)$ with i=0,..,3, we obtain $M1\,(t,d,v) = \sum_{i=0}^{3} M1_j\,(t,d,v) = \sum_{i=0}^{3} \alpha_j \left(e^{-\frac{s_i}{v\tau}} - e^{-\frac{s_i+\Delta}{v\tau}}\right)$, with $\tau = 142\,ns$ the oPs lifetime. The parameter $M1$ as a function of v (figure 2) increases at low v until it reaches a maximum, then it decreases. Given the MRD geometry, this behavior is due to the balance of two factors: on one side $M1$ decreases if v increases because the time spent by Ps in front of the slits decreases; on the other side, as v increases, Ps annihilations are also recorded by the more distant rings. In fact only when the TOF required for Ps to reach the higher ring is comparable with τ, the counting rate of the higher scintillator becomes significant. In figure 3 $M1$ as a function of t and d is reported, where $M1$ is bigger for smaller shield dimensions. The obscured zone below the *resolution* line corresponds to geometries that are not usable because the γ annihilations are directly seen by two different rings. The importance of $M1_j$ is the fact that it can be related to the measurement time. Considering that in a TOF measurement with a continuous e^+ beam 10^6 e^+/s maximum can be used to avoid false start-stop coincidence events [3] and that at least 10^5 events must be collected for each spectrum, we can estimate the acquisition time as $T_j = 10^{-1}/(M1_j \cdot \beta)\,[s]$ where $\beta(v)$ is the fraction of the implanted e^+ emitted as Ps with the desired energy [1,4].

To estimate the background noise, the distributed e^+ annihilations on the chamber walls were simulated with four γ beam sources [5] in front of each detector (numbered crosses in figure 1). For each shield configuration, the deposited energies E_i from each source i (i=0-4) in the ring j was evaluated considering the beam sources i pointing towards the ring j, in order to calculate:

$M2_j = \frac{\sum_{i \neq j, i=0}^{3} E_i}{\bar{E}}$ where $\bar{E}$ is the deposited energy from the source placed in front of the ring j.

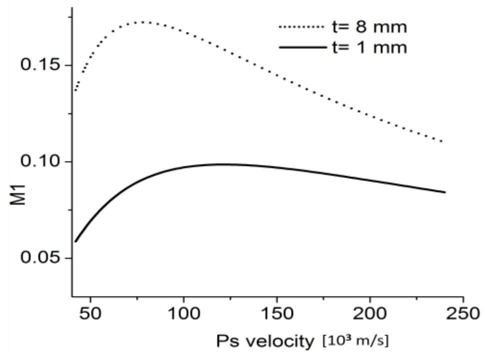

Figure 2. *M1* calculated with *d*=20 mm and *t*=8 mm and *t*=1 mm as a function of the Ps velocity

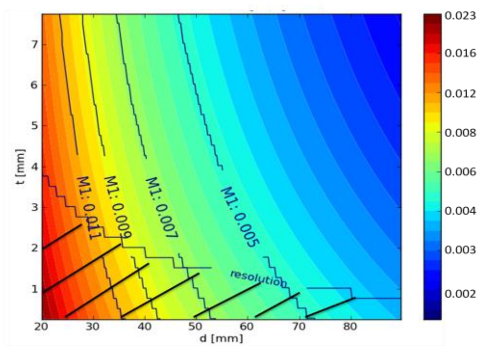

Figure 3. *M1* as a function of *t* and *d* calculated for Ps velocity of $v = 6 \cdot 10^4$ m/s

Similarly, the noise due to *cross-talk* was simulated with γ beam sources placed on the chamber axis z (numbered stars in figure 1) and pointing towards the considered ring *j*: $M3_j = \frac{\sum_{i \neq j, i=0}^{3} E_i^c}{\bar{E}}$, where E_i^c are the deposited energies in the ring j for each source i. $M2_j$ and $M3_j$ express the two effects that increase the noise of a MRD with respect to a single detector. In order to sum the two effects their relative weights have to be determined. Because the Ps emission yield depends on the sample properties and the Ps energy, while the intensity of the backscattered e^+ is connected to the e^+ beam, to the sample surface and to the set up characteristics, we can look at an experimental TOF spectrum (figure 3) carried out at Trento by using a single ring detector placed at *h*= 1 cm (figure 3). From this plot, for each Ps velocity we can extract a signal to background ratio $\delta\ (v)$ in order to obtain a new parameter $M_j = M3_j + M2_j\, /\, \delta\ (v)$ for each ring j. Thus M_j takes into account both the background and the *cross-talk* noise.

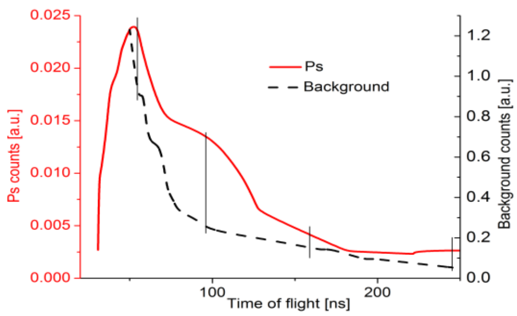

Figure 4. TOF measurement of escaping Ps in continuous line, background in dot. The vertical bars show the velocities considered as examples for calculations.

Because M_j and $T_j \propto 1/M1_j$ depend on v, also the choice of the best geometry depends on the v value that is going to be measured. As examples, we have considered four most significant values of v (corresponding to values indicated by vertical lines in figure 4): 1) $v = 2 \cdot 10^5$ m/s where the background dominates over the Ps signal, 2) $v = 1 \cdot 10^5$ m/s where $M1$ reaches its maximum 3) $v = 6 \cdot 10^4$ m/s where the background and signal are comparable, 4) $v = 4 \cdot 10^4$ m/s where the background is lower than the signal. From geometric considerations it can be observed that the ring called 1 or 2 in figure 1 are more exposed to the background and cross-talk noise. For this reason, in order to size the MRD, we have considered only the second ring, where the worst conditions in term of signal to noise ratio occur. Thus the MRD geometry must be chosen looking at the signal to noise ratio

$M1_2/M_2$, the measuring time $T_2 = \frac{10^{-1}}{M1_2 \cdot \beta}[s]$, and the spatial resolution $\Delta z = \frac{\Delta}{d}\left(\frac{d}{2} + D\right)$ (see figure 1) which is related to the resolution on the kinetic energy value E extracted by a TOF measurement by the relation: $\frac{\Delta E}{E} = \frac{2\Delta z}{z}$.

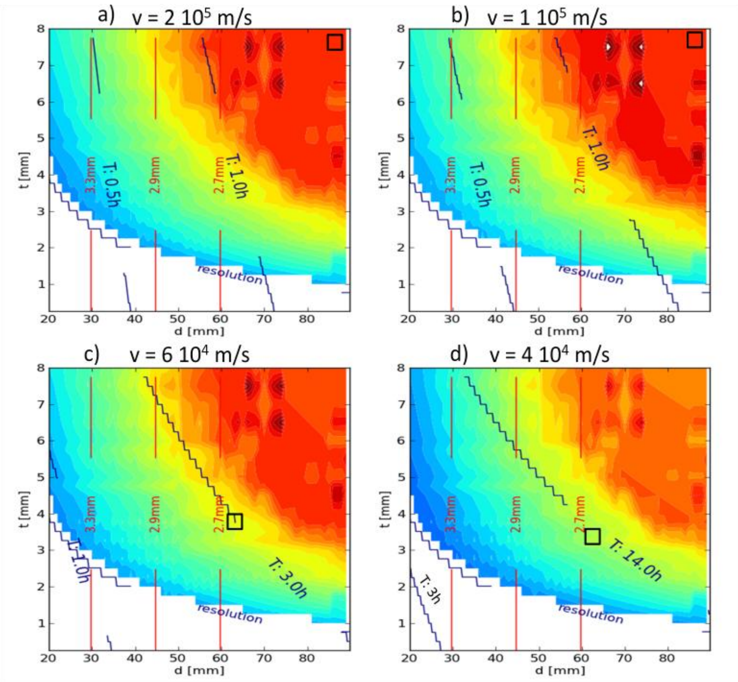

Figure 5. Colours express the value of the ratio $M1_2/M_2$, in log scale, as a function of t and d, for four different Ps velocities (the same indicated with bars in figure 3). The limitations imposed by the resolution (in the bottom) are shown. The resolution Δz on the Ps annihilation position is marked by red vertical lines and the measurement time is indicated by black lines. The squares indicate the best configuration set up as explained in the text.

The behavior of $M1_2/M_2$ with the time T_2 and the Δz values (expressed in the continuous black and red lines respectively) is shown in figure 5 for the selected four Ps velocities. To calculate T_2 the parameter β was estimated by multiplying the yield (25%) of emitted Ps as reported in [4] to the fraction (0.08, 0.06, 0.02, 0.016) calculated considering the Ps signal in figure 4. From figure 5 we can observe that the signal to noise ratio $M1_2/M_2$ increases going towards the zone in which the shield dimensions increase, because the effect of the decreasing of noise (i.e of M_2) is more relevant with respect to the decrease of $M1_2$. Thus, by imposing a limitation on the energy resolution and on the measurement time (if necessary), and optimizing the signal to noise ratio, for each velocity the best configuration can be chosen. For instance, for larger velocity, for which Ps is emitted more abundant and the measurement time is always less than 3 hours, the best set up is with higher values of t and d (see figure 5.a,b). On the contrary, when the measurement time increases, the best configuration can be chosen by imposing for instance T<3 h and Δz <2.7 mm as indicated in figure 5c. Finally, when Ps with low velocity is of interest, the measurement time increases and configurations with smaller shield are necessary (figure 5 d).

3. References

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