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COMPARISON OF DETECTOR MATERIALS FOR TIME-OF-FLIGHT POSITRON TOMOGRAPHY

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COMPARISON OF DETECTOR MATERIALS FOR TIME-OF-FLIGHT POSITRON TOMOGRAPHY

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DISCLAIMER

COMPARISON OF DETECTOR MATERIALS FOR TIME-OF-FLIGHT POSITRON TOMOGRAPHY*

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Abstract

Knowledge of detection efficiency and timing resolution is essential when comparing detector materials for time-of-flight positron tomography. We present results of Monte Carlo calculations of the detection efficiency of plastic, lead loaded plastic, NaI(Tl), liquid xenon, bismuth germanate (BGO), CsF, BaF_2, Ge, and HgI_2 for 511 keV photons. We also use recently published values of timing resolution for these detector materials to tabulate the quantity $(\text{efficiency})^2/(\text{time resolution})$ which is a measure of the relative sensitivity for time of flight positron tomography.

Introduction

Although time of flight for positron imaging was suggested by H.O. Anger in 1966,[1] its implementation was not practical until the development of CsF scintillator detectors.[2-4] Other detector materials have also been considered for this application, notably liquid xenon,[5-10] germanium,[1-13] plastic,[14-16] pure NaI (cooled),[17] mercuric iodide,[18-20] and most recently BaF_2.[21]

In order to compare detector materials for time of flight positron tomography, four primary factors must be considered:

(1) Detection Efficiency: which we define here to be the probability that an incident 511 keV photon will lose more than some threshold energy in one detector and none in any other detector. The detection efficiency depends on the density, atomic number, and dimensions of the detector, as well as the surrounding material.

(2) Timing Resolution: the accuracy with which the time difference of the arrival of two annihilation photons can be measured. For scintillators this depends on the decay time, the scintillation yield, the transfer efficiency to the photomultiplier, the quantum efficiency at the wavelength of emission, and the single photoelectron transit time jitter. For a semiconductor, the timing resolution depends on the number of electron-hole pairs created, the drift speed, the $\mu\tau$ lifetime product and the amplifier noise.

(3) The Distribution of Positron Emitter: when the emitting region is small, time-of-flight information is less valuable.

(4) Amount of Activity: at high activity levels, detector materials with good time resolution are better in rejecting accidental backgrounds.

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Scintillators

Table 1 summarizes the properties of many of the scintillation detectors used in or proposed for positron emission tomography, including the recently announced BaF_2.[21] The values for timing resolution were taken from the analysis of Tomitani[22] for liquid xenon, and from the measurements of Gariod et al[21] for BaF_2. Other information was taken from the review article by Farukhi.[23]

To compare materials with different detection efficiency and time resolution, we have defined a TOF figure of merit as the ratio:

$$(\text{efficiency})^2/(\text{time resolution})$$

Note that $(\text{efficiency})^2$ is proportional to the number of events detected and $(\text{time resolution})^{-1}$ is proportional to the statistical value of each event.

For a 30 cm emission region, and 20 mm detectors, CsF has a two-fold advantage over BGO and BaF_2 has a four-fold advantage over BGO.

The fast component of BaF_2 is due to electron-hole recombination. The best previously known example of this process is ZnO, which has a decay time of 0.4 nsec. It is hoped that a material with the detection efficiency of BGO and the speed of ZnO will be discovered. If this resulted in a detection efficiency of 80% and a time resolution of 0.2 nsec then the TOF figure merit of would be 3.2, significantly better than any material in Table 1.

TABLE 1. PROPERTIES OF SCINTILLATION MATERIALS FOR POSITRON EMISSION TOMOGRAPHY

	plastic (pilot U)	plastic (10% Pb)[a]	NaI(Tl)	liquid xenon	BGO	CsF	BaF_2
Density (gm/cm^3)	1.03	1.17	3.67	3.06	7.13	4.61	4.8
Atomic numbers	6,1	6,1,82	11,53	54	83,32,8	55,9	56,9
Hygroscopic?	NO	NO	YES	(-108°C)[b]	NO	VERY	NO
Linear attenuation coefficients at 511 keV (cm^{-1}):							
Photoelectric	0	0.008	0.060	0.061	0.393	0.087	0.085
Compton	0.096	0.106	0.268	0.215	0.510	0.334	0.353
Total	0.096	0.114	0.328	0.275	0.903	0.420	0.438
Photoelectron yield (511 keV)	730	250	2,500	≈4,000	400	150	200;800
Scintillation decay time (nsec)	1.4	2	230	2.7;27	300	2.5	0.8;630
Wavelength at max emission (nm)	432		415	180	480	390	225;310
Refractive Index	1.58		1.85		2.15	1.48	1.56
Photoelectrons/nsec	500	180	11	?	1.3	60	250;1.3
Pulse height resolution (FWHM)	-	-	7%		12%	25%	13%
Pulse height threshold (keV)	100	100	100	100	400	100	100
Time resolution (FWHM nsec)[c]	0.2	0.4	1.5	0.2	5	0.4	0.3
Detection efficiency[c]	20%	22%	49%	49%	77%	50%	60%
TOF Figure of merit[d]	0.20	0.12	0.16	1.2	0.3[e]	0.6	1.2

[a]Pilot PS/Pb with 10% Pb by weight (mole fraction 0.627%)
[b]Boiling point at 1 atm pressure
[c]For a 20 mm x 20 mm x 40 mm deep detector and threshold as given. Packing fractions of 95% for plastic, BGO, and BaF_2, 90% for NaI(Tl), 80% for CsF, and 100% for liquid Xenon have been assumed.
[d]TOF figure of merit= $(\text{efficiency})^2/(\text{time resolution})$
[e]time resolution of 2 nsec used to correspond to a 30 cm diam phantom

Semiconductors

Table 2 summarizes the properties of several semiconductor detector materials for application in TOF positron emission tomography. The time resolution for Germanium was taken from the measurements of Kaufman[12] and the calculations of Llacer.[13] Compared to Germanium, all heavy atom semiconductors thus far known have lower mobility and much shorter trapping lengths.[24] In table 2, E is the electric field (V/cm), μ is the carrier mobility (cm/sec per V/cm), and τ is the trapping time constant.

None of the three entries in Table 2 provide any TOF figure of merit advantage over the best scintillators of table 1, but it is important to note that the semiconductors naturally achieve high spatial resolution. In fact, narrow detectors have better time and pulse height resolution than wider detectors.

Detection Efficiency

The computer code used in this calculation (described previously)[25] traces the Compton and photoelectric interactions of 511 keV photons incident on an infinite linear array of detectors (Figure 1). The program assumes that the face of one detector is uniformly illuminated. The Compton and photoelectric cross sections were derived from the tabulation of Plechaty et al for the individual elements.[26] Results are presented in Table 3.

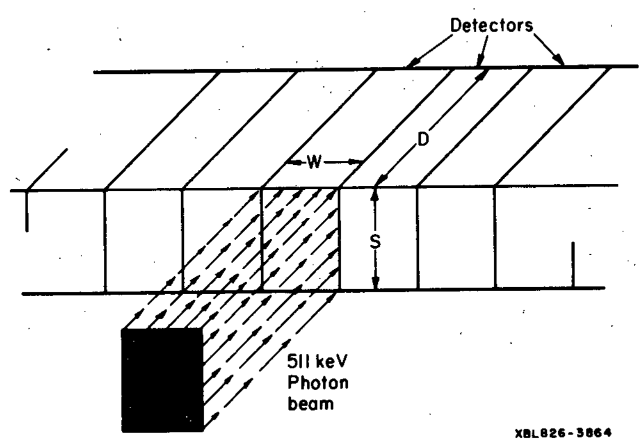

Figure 1: Schematic of detector array and beam geometry for Monte Carlo calculation of detection efficiency.

The efficiencies in table 3 must be multiplied by the packing fraction, which depends on the specific detector design. This rule holds for incident angles up to about 10°. For large angles the effective packing fraction approaches unity and is determined by the relative stopping power of the detector and packing material. As NaI(Tl) and CsF

TABLE 2. PROPERTIES OF SEMICONDUCTOR MATERIALS FOR POSITRON EMISSION TOMOGRAPHY

	Ge	HgI_2	CdTe
Density	5.38	6.3	6.2
Atomic number	32	80,53	48,52
Linear attenuation coefficients at 511 keV (cm^{-1}):			
Compton attenuation (cm^{-1})	0.407	0.442	0.441
Photoelectric attenuation (cm^{-1})	0.019	0.269	0.098
Total	0.426	0.711	0.539
Band gap (eV)	0.66	2.22	1.50
Electron mobility μ (cm/sec per V/cm)	4500	94	1050
Hole mobility μ (cm/sec per V/cm)	3500	4	80
Typical electric field E (V/cm)	5,000	40,000	2,000
Electron transit time (ns/mm)	10	30	50
Hole transit time (ns/mm)	10	600	600
$\mu\tau$ (electrons)	>1	1×10^{-4}	1×10^{-1}
$\mu\tau$ (holes)	>1	1×10^{-5}	8×10^{-1}
Trapping distance $E\mu\tau$ (electrons) (cm^{-1})	$>10^4$	4 cm	2 cm
Trapping distance $E\mu\tau$ (holes) (cm^{-1})	$>10^4$	0.4 cm	0.2 cm
Number of e-hole pairs	170,000	70,000	110,000
Pulse height resolution	≃1%	≃5%	≃5%
Time resolution	0.4 nsec	2 nsec?	0.8 nsec?
Pulse height threshold (keV)	100	400	100
Detection efficiency[a]	53%	70%	66%
Figure of merit for TOF	0.70	0.25	0.54

[a]For a 20 mm x 20 mm x 40 mm deep detector and threshold as given. Packing fraction 95%.

detectors require encapsulation, their packing fraction is fairly low, from 70% to 85% for large (20 mm detectors) and less for smaller sizes. On the other hand, reflectors for non-hygroscopic materials can be as thin as 0.1 mm which results in packing fractions very close to unity.

Although the detectors should be as small as possible, there is little advantage in making them much smaller than other factors limiting spatial resolution. The most important of these are deviations from 180°,[27] which contribute about 0.8 mm FWHM for a 50 cm detector ring and 1.6 mm FWHM for a 100 cm detector ring and positron range, which contributes a non-Gaussian broadening that extends over several mm, depending on the energy of the positron emitter.[28] Ideally, the quantitation volumes in the reconstructed multi-slice images should be cubes, as there is no reason to assume that anatomical features are elongated in any preferred direction. From a practical standpoint, however, there are several reasons why many positron tomographs have detectors that are elongated along the axial dimension S:

(1) If only nearest neighbor cross-coincidences are used, the sensitivity of each slice is proportional to S^2.

(2) On the other hand, if all possible cross-coincidences are used and the frontal area of the detectors is kept constant, then the overall sensitivity is nearly independent of detector shape. Under these conditions, making the detectors longer in the axial direction (and narrower in the in-plane direction) decreases the number of slices to be stored and reconstructed and actually increases the total number of quantitation voxels.

Table 4 combines our calculations of the detection efficiency for BaF_2 as a function of crystal depth and pulse height threshold with the corresponding time resolution measurements of Gariod et al[21] to investigate how the TOF figure of merit depends on these factors. While these results seem to indicate that it is best to use long crystals and a low pulse height threshold, firm conclusions should be based on the more accurate approach of measuring both detection efficiency and timing resolution in a realistic test set-up.

Conclusions

The best detector material for TOF positron emission tomography at present is BaF_2, which of the seven scintillators and three semiconductors considered here has the largest TOF figure of merit. BaF_2 is not the ultimate material, however, as a nonhygroscopic material with the detection efficiency of BGO and the speed of ZnO would have a TOF figure of merit three times larger than that of BaF_2.

TABLE 3. DETECTION EFFICIENCIES[a]

W (mm)	S (mm)	D (mm)	plastic	plastic (10% Pb)[b]	NaI(Tl)	liquid xenon	BGO	CsF	BaF_2	Ge	HgI_2
2	2	10	7%(0%)	8%(1%)	20%(6%)	19%(7%)	47%(31%)	24%(8%)	26%(8%)	23%(2%)	40%(23%)
		20	12%(0%)	15%(2%)	35%(11%)	32%(11%)	66%(45%)	41%(14%)	42%(14%)	39%(3%)	60%(35%)
		30	17%(0%)	22%(2%)	45%(13%)	42%(15%)	75%(51%)	52%(18%)	52%(18%)	50%(4%)	69%(41%)
		40	23%(0%)	26%(3%)	53%(16%)	49%(17%)	79%(54%)	59%(20%)	60%(20%)	55%(5%)	73%(43%)
		50	26%(0%)	31%(3%)	58%(18%)	54%(19%)	79%(54%)	64%(22%)	65%(22%)	59%(5%)	76%(46%)
		∞	69%(0%)	70%(8%)	71%(21%)	73%(25%)	80%(55%)	72%(25%)	72%(24%)	69%(6%)	78%(46%)
2	5	10	6%(0%)	7%(1%)	19%(6%)	17%(6%)	45%(33%)	24%(9%)	24%(8%)	23%(2%)	37%(26%)
		20	11%(0%)	14%(2%)	33%(11%)	29%(11%)	63%(48%)	38%(15%)	39%(14%)	36%(4%)	55%(38%)
		30	17%(0%)	20%(2%)	42%(15%)	38%(15%)	70%(54%)	48%(20%)	47%(19%)	44%(5%)	64%(44%)
		40	21%(0%)	25%(3%)	49%(17%)	47%(18%)	73%(56%)	54%(22%)	54%(21%)	50%(5%)	69%(47%)
		50	26%(0%)	30%(3%)	54%(19%)	51%(20%)	75%(58%)	58%(25%)	58%(24%)	54%(6%)	70%(48%)
		∞	67%(0%)	68%(8%)	66%(23%)	68%(27%)	75%(57%)	66%(27%)	66%(26%)	61%(7%)	73%(49%)
5	5	10	7%(0%)	8%(1%)	20%(7%)	18%(7%)	49%(37%)	25%(10%)	26%(11%)	24%(3%)	41%(28%)
		20	13%(0%)	14%(2%)	34%(12%)	31%(12%)	69%(53%)	42%(17%)	41%(17%)	39%(5%)	60%(41%)
		30	17%(0%)	21%(3%)	45%(17%)	41%(17%)	76%(59%)	51%(22%)	52%(22%)	48%(6%)	71%(50%)
		40	22%(0%)	26%(3%)	52%(19%)	48%(20%)	81%(63%)	58%(25%)	59%(25%)	55%(6%)	75%(53%)
		50	26%(0%)	31%(4%)	57%(21%)	54%(22%)	82%(64%)	63%(27%)	63%(26%)	59%(8%)	77%(55%)
		∞	68%(0%)	70%(9%)	71%(26%)	73%(30%)	83%(66%)	71%(32%)	72%(31%)	66%(9%)	79%(56%)
5	10	10	7%(0%)	8%(1%)	20%(8%)	17%(7%)	47%(39%)	25%(11%)	25%(11%)	21%(3%)	39%(29%)
		20	12%(0%)	14%(2%)	32%(14%)	28%(13%)	68%(57%)	38%(19%)	39%(19%)	35%(6%)	58%(45%)
		30	17%(0%)	19%(3%)	42%(18%)	39%(18%)	75%(64%)	48%(25%)	49%(24%)	44%(7%)	68%(53%)
		40	21%(0%)	25%(3%)	48%(21%)	45%(20%)	78%(67%)	54%(29%)	55%(27%)	49%(8%)	72%(57%)
		50	25%(0%)	30%(4%)	54%(25%)	51%(23%)	80%(68%)	59%(30%)	57%(30%)	53%(9%)	74%(58%)
		∞	66%(0%)	66%(9%)	65%(29%)	66%(32%)	81%(69%)	66%(35%)	65%(34%)	59%(10%)	76%(60%)
10	10	10	7%(0%)	8%(1%)	21%(9%)	18%(8%)	50%(41%)	25%(13%)	27%(13%)	24%(4%)	41%(30%)
		20	12%(0%)	15%(2%)	35%(16%)	31%(15%)	71%(60%)	42%(22%)	43%(22%)	39%(7%)	63%(49%)
		30	17%(0%)	20%(3%)	45%(21%)	41%(20%)	80%(68%)	52%(28%)	53%(27%)	48%(9%)	72%(57%)
		40	22%(0%)	25%(4%)	53%(25%)	49%(24%)	84%(73%)	60%(32%)	59%(32%)	53%(10%)	77%(62%)
		50	26%(0%)	30%(4%)	57%(26%)	54%(26%)	85%(73%)	64%(35%)	65%(35%)	58%(12%)	81%(65%)
		∞	67%(0%)	69%(10%)	72%(34%)	73%(36%)	87%(75%)	73%(41%)	73%(40%)	66%(13%)	84%(67%)
10	20	10	6%(0%)	8%(1%)	20%(9%)	17%(9%)	50%(43%)	24%(13%)	26%(13%)	23%(5%)	41%(33%)
		20	11%(0%)	14%(2%)	32%(16%)	30%(16%)	71%(64%)	40%(24%)	41%(24%)	35%(8%)	61%(52%)
		30	16%(0%)	19%(3%)	43%(23%)	39%(22%)	80%(73%)	49%(31%)	51%(31%)	43%(11%)	72%(62%)
		40	21%(0%)	25%(4%)	49%(27%)	46%(26%)	84%(77%)	56%(36%)	56%(36%)	48%(13%)	77%(67%)
		50	25%(0%)	28%(5%)	55%(31%)	51%(30%)	84%(78%)	59%(38%)	61%(39%)	51%(15%)	79%(69%)
		∞	62%(0%)	62%(11%)	66%(39%)	67%(40%)	86%(78%)	68%(45%)	67%(45%)	57%(18%)	81%(71%)
20	20	10	7%(0%)	7%(1%)	21%(10%)	18%(9%)	52%(45%)	26%(14%)	27%(14%)	24%(5%)	42%(33%)
		20	12%(0%)	15%(2%)	36%(19%)	33%(18%)	75%(67%)	42%(26%)	45%(27%)	40%(11%)	66%(55%)
		30	18%(0%)	20%(3%)	47%(26%)	42%(24%)	85%(78%)	54%(35%)	56%(36%)	50%(16%)	76%(66%)
		40	21%(0%)	26%(5%)	54%(31%)	49%(28%)	88%(81%)	62%(41%)	63%(41%)	56%(18%)	84%(74%)
		50	25%(0%)	30%(5%)	61%(35%)	55%(33%)	90%(84%)	67%(45%)	68%(46%)	61%(20%)	85%(75%)
		∞	65%(0%)	67%(13%)	74%(44%)	76%(48%)	91%(84%)	77%(54%)	77%(53%)	69%(24%)	88%(78%)

[a]Valid detections require more than 100 keV energy loss in one detector and less than 10 keV in each of the other detectors. Percentages in parentheses are for full 511 keV energy loss in one detector. 10,000 photons per run, 0° incidence.
All efficiencies must be reduced by the packing fraction which depends on the specific detector design.
[b]10% by weight. Mole fraction is 0.627%

TABLE 4. EFFECT OF BaF_2 CRYSTAL DEPTH AND PULSE HEIGHT THRESHOLD ON EFFICIENCY AND TIMING RESOLUTION[a]

Pulse height threshold	Depth D (mm)	Detection efficiency	Time resolution (nsec FWHM)[b]	TOF Figure of merit
150 keV	10	22%	0.20	0.25
	20	39%	0.22	0.68
	30	49%	0.25	0.96
	40	56%	0.28	1.14
	50	62%	0.30	1.27
photopeak	10	13%	0.16	0.11
	20	27%	0.18	0.40
	30	35%	0.20	0.62
	40	42%	0.23	0.76
	50	46%	0.25	0.86

[a]Crystals with 24 mm x 24 mm front face and a packing fraction of 95%
[b]Values derived from the measurements of Gariod, Allemand, Cormoreche, and Laval, Reference 21, Figure 5.

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