Estimating the efficiency and purity for detecting annihilation and prompt photons with J-PET using toy Monte Carlo simulation.

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Motivation

- Recently reported first positronium images [1] inspire the development of methods for the registration of three photons from $\beta^+ + \gamma$ radionuclides.
- The Positronium Imaging ($\beta^+ + \gamma$) technique represents a potential enhancement of the PET imaging method and its core principle involves employing a β^+ radiation source that emits additional gamma (γ) quanta referred to as prompt gamma [2].
- Each isotope has unique emission characteristics and energy levels. Understanding the efficiency and purity of specific isotopes is crucial for optimizing Positronium imaging techniques.

Physical properties of the isotopes

Isotope	$T_{1/2}$	Y_{β^+} (%)	E_{max} (MeV)	R_{min} (mm)	E_γ (MeV)	Y_γ (%)	$Y_{\beta^+ + \gamma}$ (%)	$Y_{\frac{\beta^+ + \gamma}{\beta}}$ (%)	Delay (ps)	Comp. E. (MeV)
^{22}Na	2.60 y	89.95	0.545	0.54	1.275	99.94	89.90	99.94	3.6	1.062
^{44}Sc	3.97 h	94.3	1.474	1.69	1.157	99.9	94.3	100	2.61	0.948
^{68}Ga	67.71 m	88.91	1.899	2.25	1.077	3.22	1.19	1.34	1.57	0.870
^{60}Cu	23.7 m	92.59	0.653	0.67	1.333	88	81	87.48	0.735	1.118
					1.791	45.4	42	45.36	-	1.567
					0.826	21.7	20.4	22.03	0.59	0.631
^{72}As	26.0 h	87.86	3.33	4.27	0.834	81	71	80.81	3.35	0.638
^{82}Rb	1.26 m	95.36	3.382	4.34	0.777	15.1	13.5	14.16	4.45	0.584
^{55}Co	17.53 h	75.89	1.5	1.72	0.931	75	59	77.74	8	0.731
					0.477	20.2	13.5	17.79	37.9	0.311
					1.409	16.9	11.3	14.89	37.9	1.192
^{124}I	4.17 d	22.69	1.822	2.15	0.603	62.9	12	52.89	6.2	0.423
					0.723	10.36	0.25	4.58	1.04	0.534
^{10}C	19.3 s	99.97	2.93	3.69	0.718	100	99.97	100	710	0.530
^{14}O	70.6 s	99.89	1.808	2.13	2.313	99.39	99.26	99.38	0.068	2.083

Table 1: The table incorporates information on the physical properties of all the isotopes [3, 4]

Method

- Klien Nishna formula for electron energy distribution

$$\frac{d\sigma}{d\Delta E} = \frac{r_0^2 mc^2}{(E_0 - \Delta E)^2}\left\{\left[\frac{mc^2 \Delta E E_0^2}{E_0^2}\right] + 2\left[\frac{E_0 - \Delta E}{E_0}\right]^2 + \frac{E_0 - \Delta E}{E_0^3}[(\Delta E - mc^2)^2 - (mc^2)^2]\right\} \quad (1)$$

- Maximum energy attainable by an electron

$$\Delta E_{max} = E_0\left[1 - \frac{1}{1 + 2\frac{E_0}{mc^2}}\right] \quad (2)$$

- The fractional energy resolution of the J-PET detector [5]

$$\frac{\sigma(\Delta E)}{\Delta E} = \frac{0.044}{\sqrt{\Delta E(MeV)}} \quad (3)$$

- Figure of Merit (FoM)

$$FOM = \mathcal{E}_a \times \mathcal{E}_p \times P_a \times P_p \quad (4)$$

Materials

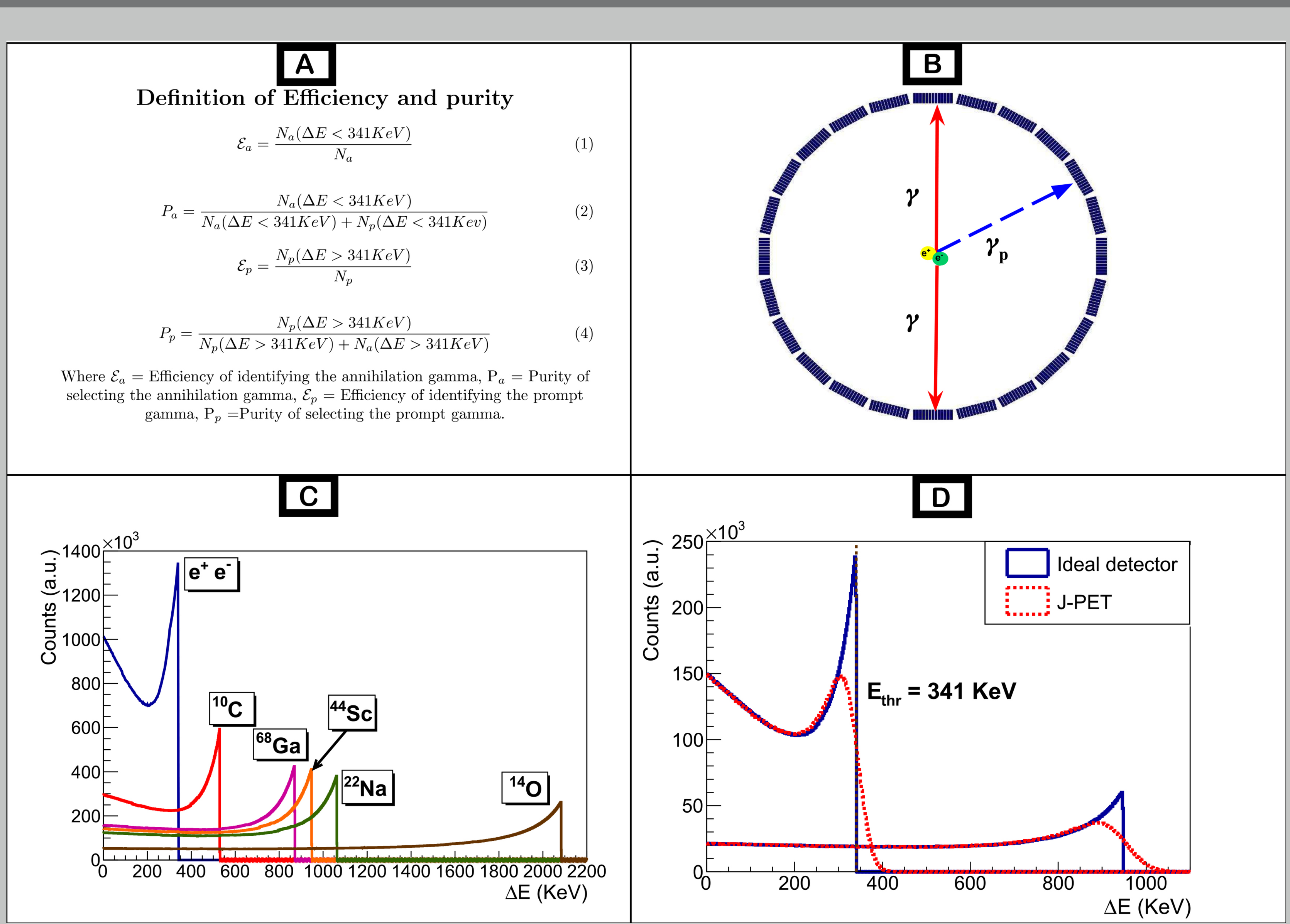

Figure 1: (A) Definition of efficiency and purity for the case when the fractional energy resolution is incorporated (B) Schematic view of the modular J-PET with an exemplary two annihilation gamma (γ) and one prompt gamma (γ_P) event. (C) Simulated energy loss spectra for various isotopes (D) Effect of the fractional energy resolution for ^{44}Sc

Results

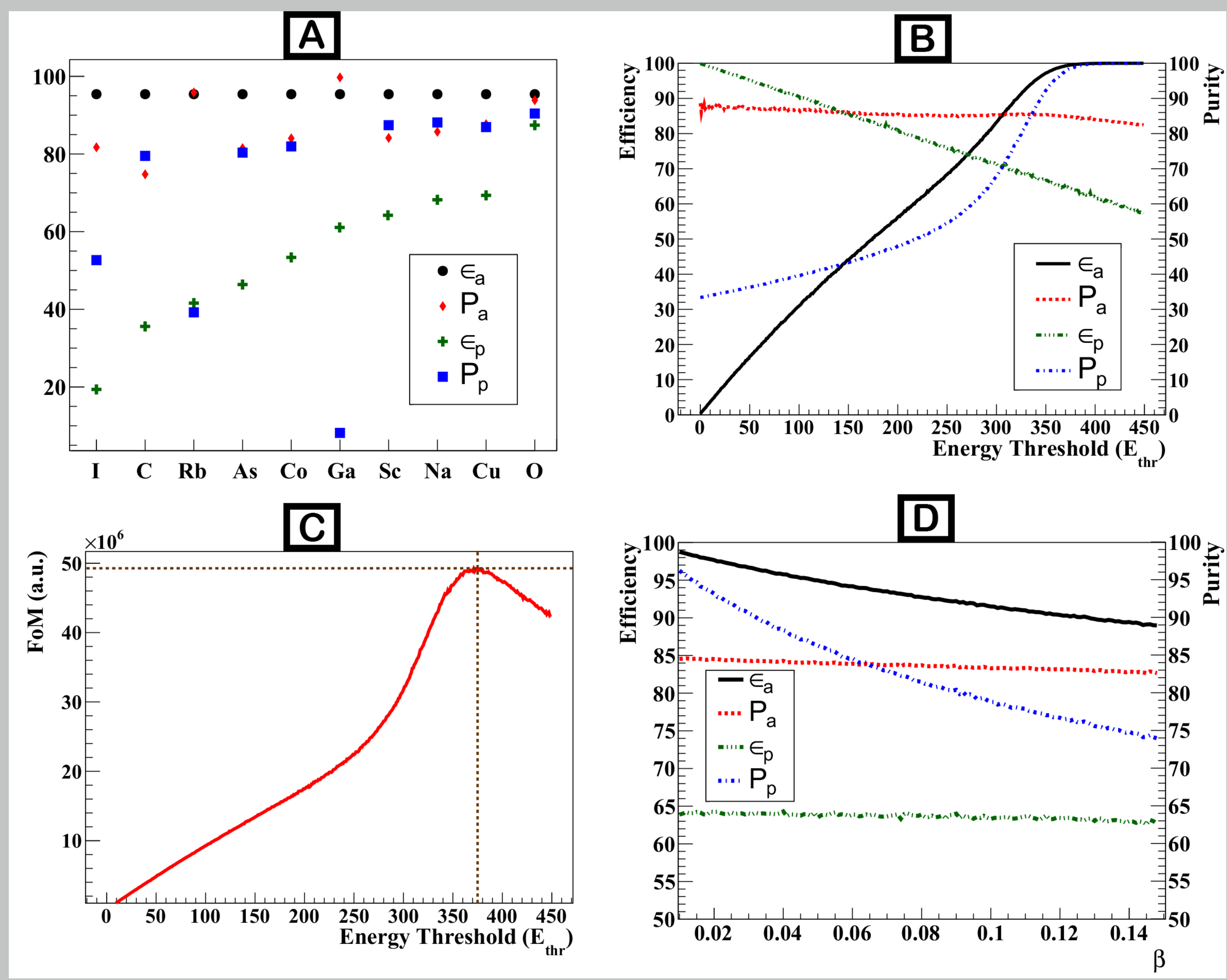

Figure 2: (A) Efficiency and purity measurements for different isotopes with an energy threshold set at 341 KeV. (B) Efficiency/purity versus Energy threshold for ^{22}Na. (C) FoM versus energy threshold for ^{44}Sc. (D) Efficiency/purity dependence on fractional energy resolution for ^{44}Sc.

Isotopes	E_γ (MeV)	T_{opt} (KeV)	$\mathcal{E}_a$ (%)	P_a (%)	$\mathcal{E}_p$ (%)	P_p (%)
^{22}Na	1.275	373	99.42	85.07	65.09	98.25
^{44}Sc	1.157	375	99.51	83.38	60.34	98.41
^{68}Ga	1.077	410	99.98	99.69	54.78	96.73
^{60}Cu	1.333	376	99.54	87.30	66.9	98.46
	1.791	390	99.88	95.06	77.14	99.32
	0.826	383	99.76	93.72	39.32	94.77
^{72}As	0.834	367	99.07	80.92	42.20	94.81
^{82g}Rb	0.777	387	99.83	95.51	33.78	93.54
^{55}Co	0.931	375	99.49	83.33	48.80	97.43
	0.477	125	37.71	91.33	59.76	7.86
	1.409	395	99.93	97.61	67.14	98.6
^{124}I	0.603	360	98.49	81.40	14.9	72.29
	0.723	409	99.99	99.58	24.04	90.92
^{10}C	0.718	357	98.15	74.36	32.34	89.71
^{14}O	2.313	389	99.86	93.14	85.19	99.68

Table 2: Table summarising the values for optimized threshold (T_{opt}) and corresponding efficiency and purity for annihilation and prompt gamma for different isotopes.

Summary

1. Identifying Ideal Candidates for Positronium Imaging
2. Obtained the optimum energy threshold for different isotopes

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