Multi-photon decay mode spectroscopy of positronium

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Positronium is a system consisting of an electron and its anti-particle, a positron, bound together into an exotic atom, specifically an onium. The system is unstable: the two particles annihilate each other to predominantly produce two or three gamma rays, depending on the relative spin states. Energy and momentum conservation forbid annihilation to a single photon, with no constraints on higher order multiplicities at greatly decreased probability. The branching ratio for decays producing four or more photons is on the order <10^{-6}. Experiments using ^{22}Na as a source of positrons of various intensities have been measured with an array of eight $LaBr_3$:Ce scintillation detectors. These detectors combine good energy resolution (40 keV FWHM at 511 keV) with excellent timing resolution (~300 ps) which allow for high quality photon time-of-flight measurements. From these measurements, the branching ratio for the next-to-leading order decay (four photon decay) of parapositronium (p-Ps) is estimated, and comparisons are drawn with previous results from similar measurements, as well as its theoretically-obtained value $\mathrm{BR}(\text{p-Ps} \rightarrow 4\gamma) \approx 1.49 \times 10^{-6}$.

Experimental set-up

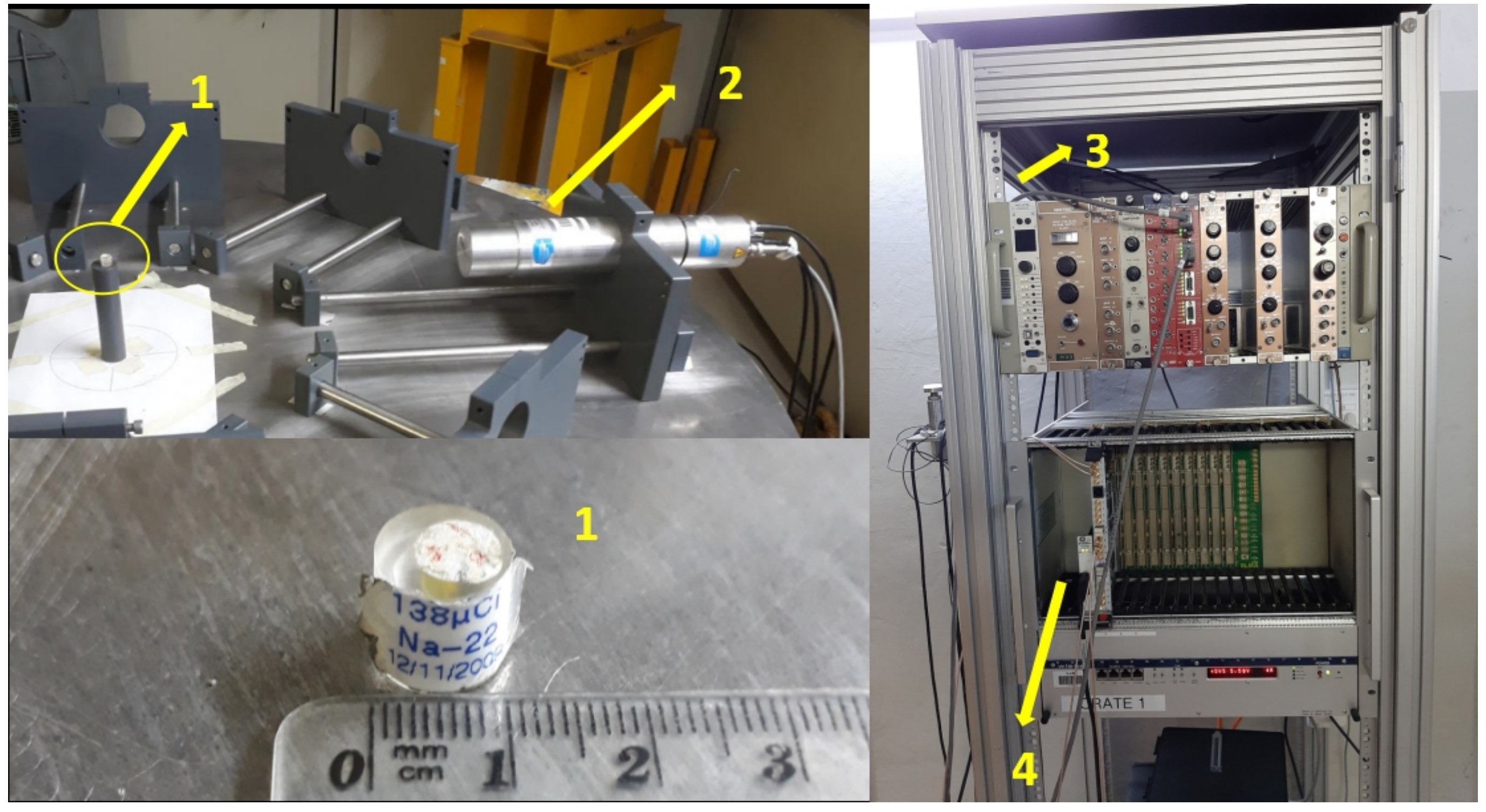


Figure 1: *^{22}Na source* (1) placed a measured distance away from a 2"x2" LaBr3:Ce detector (2). The detector photomultiplier is operated with the high voltage (HV) source (3), while the energy and timing signals are digitised and processed through with 500MHz, 16 channel digital signal processor (4).*

The detectors

- 2"x2" $LaBr_3$:Ce scintillator [1]
- excellent energy resolutions
- high count rate capabilities

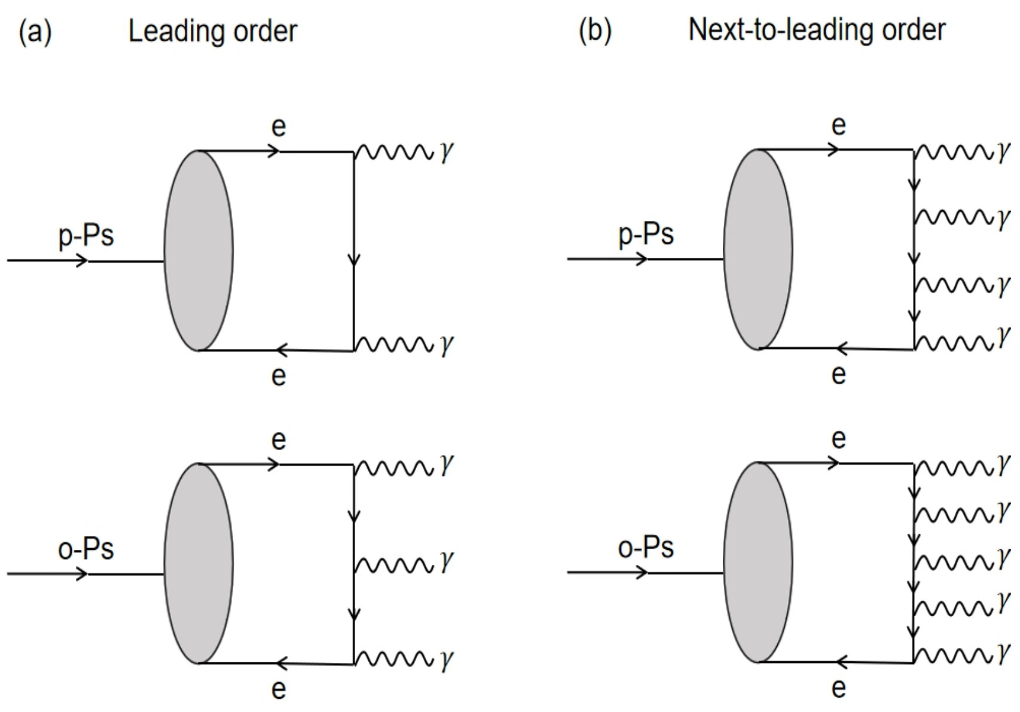
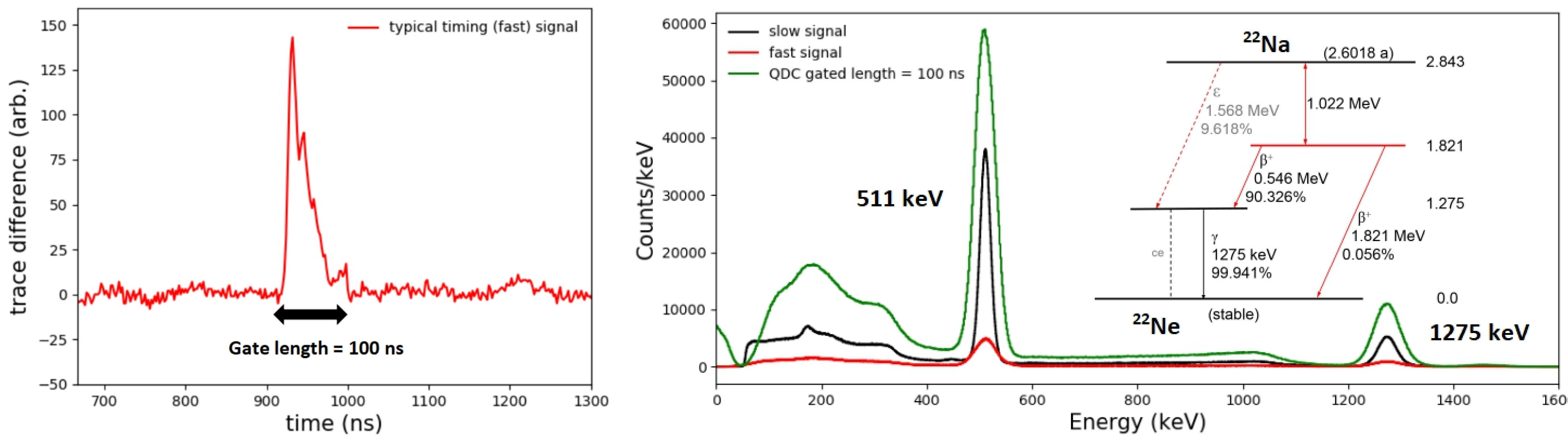


Figure 2: *Decay schemes for the (a) leading order, and (b) next-to-leading order annihilations of p-Ps and o-Ps.*

Minimisation of energy resolutions

Figure 3: *Typical fast signal obtained shown with a QDC gate length of 100 ns (left). ^{22}Na energy spectra for the slow and fast signals, and the QDC gated spectrum (right).*



QDC gate length (ns)	Energy resolution of 511 keV peak (%)
100	9.08 (10)
150	10.61 (10)
200	11.77 (81)
250	13.0 (21)
300	14.5 (79)

Table 1: *Energy resolution of the 511 keV peak as a function of the setting of gate length of the QDC. A minimal energy resolution is achieved with a gate length of 100 ns.*

- QDC converts the integrated charge from the detector (which is related to the total detected energy) to a digitised signal
- Limits of integration of the current is adjusted by the gate length
- Gate lengths <100 ns were found to not capture the full signal
- Gate lengths >100 ns were found to reduce energy resolution

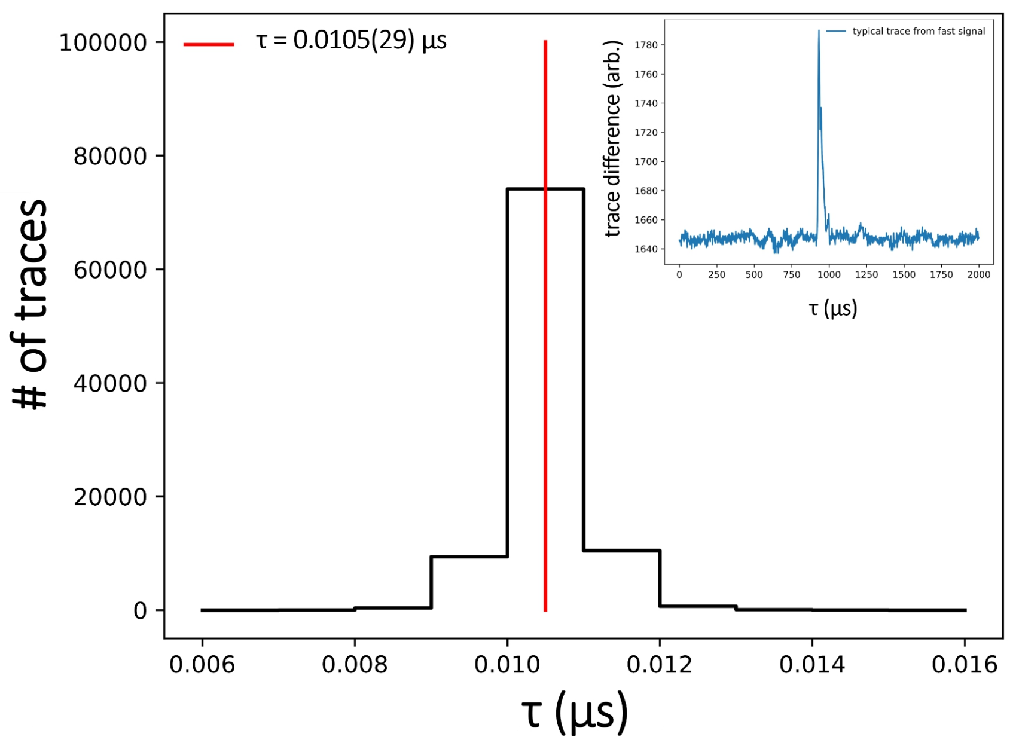


Figure 4: *Traces from the timing (fast) signals from the detector binned into their fitted decay constant values.*

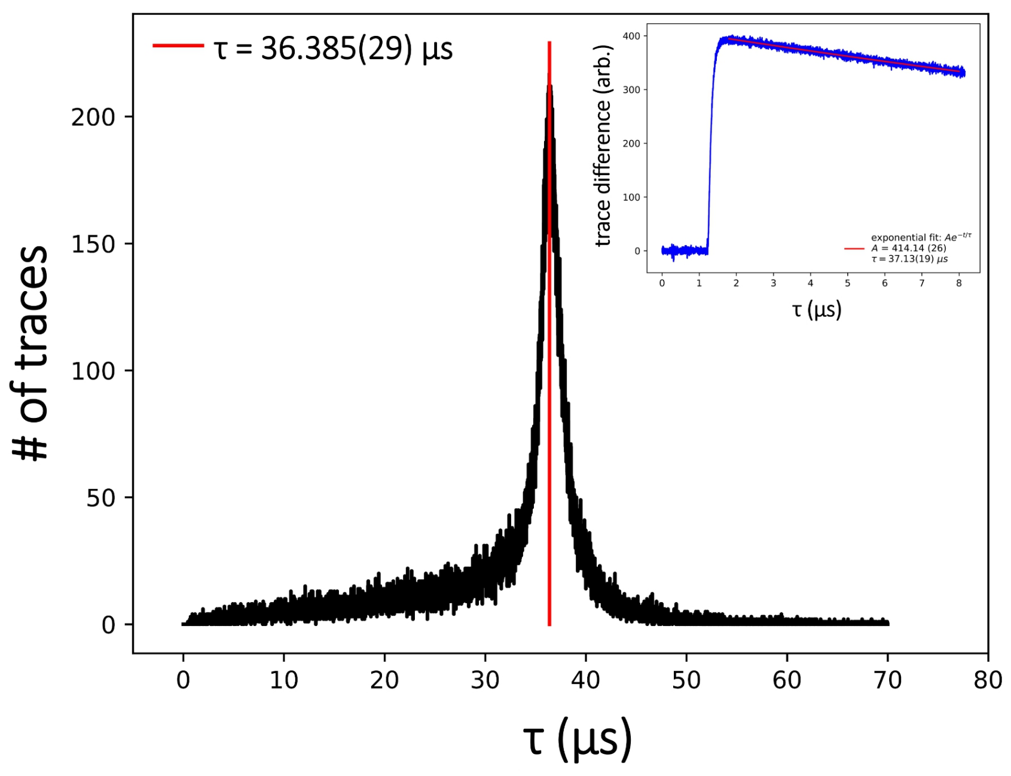


Figure 5: *Traces from the energy (slow) signals from the detector binned into their fitted decay constant values.*

Decay constant values are binned for the fast and slow detector signals

Fast signals - characterised by smaller τ values (~10 ns)

Slow signals - characterised by larger τ values (~35 µs)

The most frequently occurring τ values indicate the τ value setting that will result in a minimal energy resolution

Data reduction and multiplicity spectra

- Need to distinguish between 4γ events from measured data
- There are two basic requirements:
  - **T_c** - Coincident γ's must have a time difference within 2 ns
  - **E_c** - Sum energy of γ's in the event ~1.022 MeV
- Multiplicity spectra are generated using E_c and T_c as filtering conditions
- Events are catergorised into $\mathcal{M}$ bins, which represent the detector pairs that measure the gated events

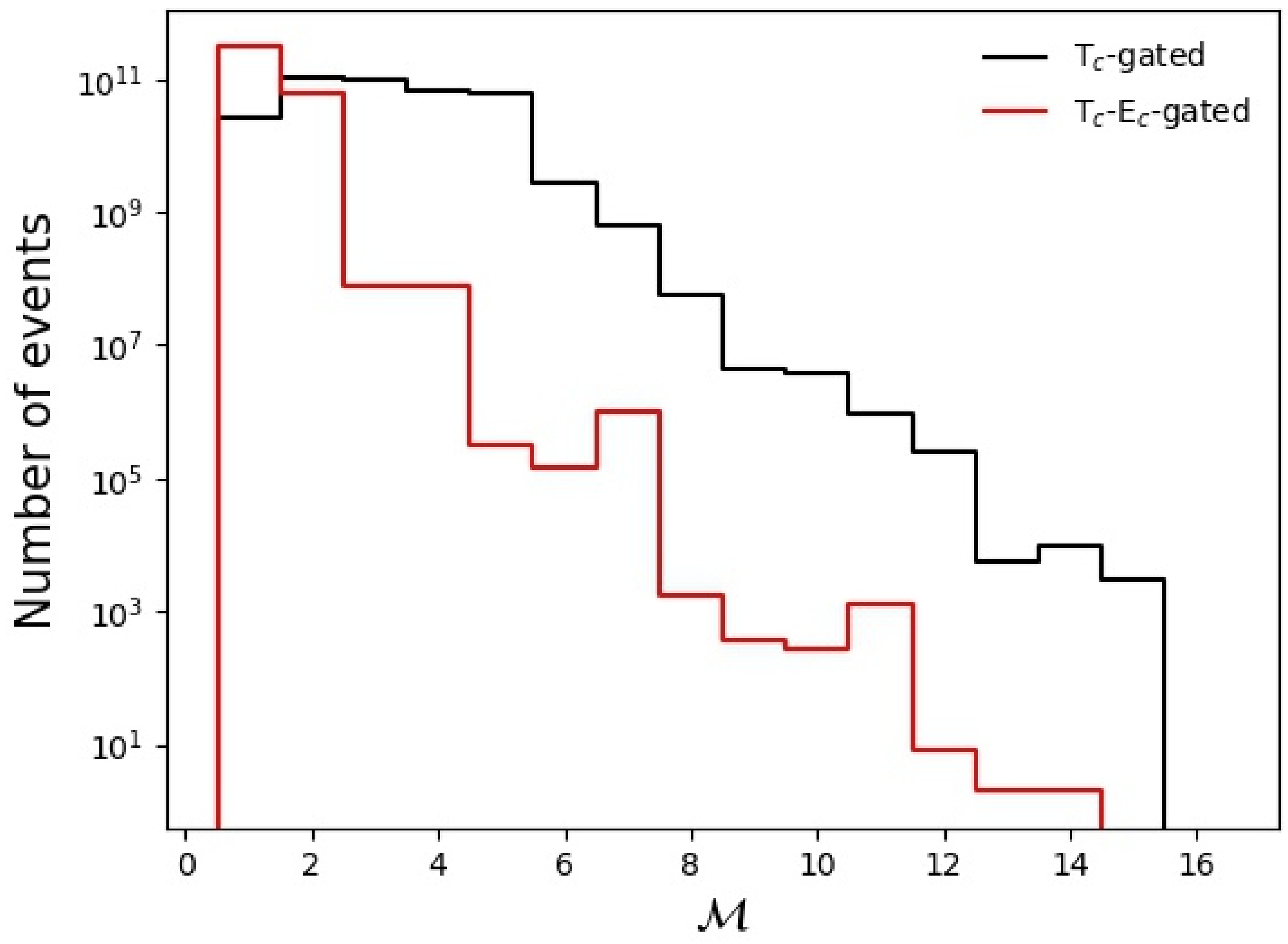


Figure 6: *Multiplicity spectra generated using E_c as the energy gate and T_c as the time gate.*

$\mathcal{M}$	T_c-E_c-gated bin value
1	3.02×10^{11}
6	1.45×10^{5}

Table 2: *Bin $\mathcal{M}$=1 corresponds to number of 2γ events detected, while bin $\mathcal{M}$=6 corresponds to number of 4γ events detected.*

Branching ratio calulation [2]

$$\mathrm{BR}_{4\gamma} = \frac{(N_{4\gamma} - B_{4\gamma})\epsilon_{2\gamma}}{N_{2\gamma}\epsilon_{4\gamma}}$$

Symbols

$N_{4\gamma/2\gamma}$ - number of $4\gamma/2\gamma$ events detected

$B_{4\gamma}$ - expected number of 4γ background events

$\epsilon_{4\gamma/2\gamma}$ - detection efficiency of detector array for $4\gamma/2\gamma$ annihilations

Calculation

- $N_{2\gamma} = 3.02 \times 10^{11}$
- $N_{4\gamma} = 1.45 \times 10^{5}$
- $\epsilon_{2\gamma} = 2.9\,(4) \times 10^{-2}$
- $\epsilon_{4\gamma}$, $B_{4\gamma}$ are unknown, and are typically obtained through Monte Carlo simulations

Approximation of result:

$$\mathrm{BR}_{4\gamma} \sim \frac{N_{4\gamma}}{N_{2\gamma}} = 5 \times 10^{-7}$$

Acknowledgments

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South African Institute of Physics Conference 2021 (SAIP2021), North-West University, South Africa. 22-30 July 2021

References:
** iThemba LABS is the sole producer of ^{22}Na sources in the world!*
[1] detectors supplied by Saint-Gobain Crystals - https://www.crystals.saint-gobain.com/products/standard-and-enhanced-lanthanum-bromide
[2] Equation obtained from Vetter & Freedman, Branching-ratio measurements of multiphoton decays of positronium, Physical Review A, 66(5):052505, November 2002