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Full Length Article

Response of the FAst TIMing Array (FATIMA) for DESPEC at FAIR Phase-0

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ABSTRACT

The Monte-Carlo simulated response for γ-ray detection of the FAst TIMing Array (FATIMA) for exploitation within the DEcay SPECtroscopy (DESPEC) experimental system at the FAIR Phase-0 facility at Darmstadt, Germany is presented. In this configuration, FATIMA consisted of 36 $LaBr_3$(Ce) detectors surrounding the AIDA, position-sensitive charged-particle active stopper. The decay of the $I^{\pi}=8^{+}$ isomer-fed decay cascade in ^{96}Pd, measured in the first DESPEC experiment at the FAIR-0 facility was used to validate the simulations. The experimental data yielded in-situ full-energy peak efficiency values for FATIMA of 11.2(11)%, 6.8(7)%, 3.8(4)% and 2.1(4)% at 106, 325, 684 and 1415 keV respectively, consistent with the values derived from the simulated response.

1. Introduction

The DESPEC (DEcay SPECtroscopy) radiation detection setup at the FAIR-0 GSI facility [1–3] is a state-of-the-art detection system where a number of experiments have been performed to measure isomeric and beta-delayed spectroscopy in exotic radioisotopes [4,5]. The first γ-ray detection setup at DESPEC (Fig. 1), consisted of an array of $LaBr_3$(Ce) scintillation detectors from the FAst TIMing Array (FATIMA) collaboration [6] used in conjunction with seven, three-element, Galileo Triple Cluster (GTC) high-purity germanium detectors [7]. This short paper presents results from Monte-Carlo modelling of the FATIMA and compares these with experimentally derived values using in-situ coincidence to singles gamma-ray intensity ratio measurements.

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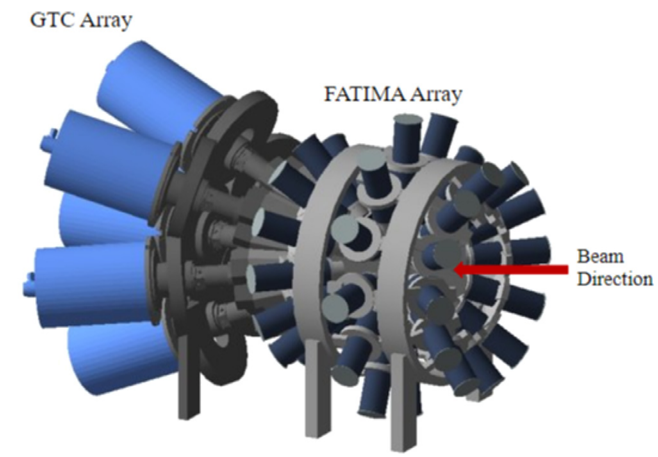

Fig. 1. The NPTool simulation representation of the DESPEC setup including the 36 $LaBr_3$(Ce) detectors from FATIMA in the current work.

The FATIMA used for the first DESPEC experimental campaign consisted of 36 individual $2'' \times 1.5''$ $LaBr_3$(Ce) detectors with a typical measured full width at half maximum energy resolution of 3.4 keV at 662 keV [6]. These γ-ray detectors surrounded the Advanced Implantation Detector Array (AIDA) active stopper [8], made up of three stacked Double Sided Silicon Strip Detectors (DSSSDs), sandwiched between two fast-plastic β-particle detectors [9] in the first DESPEC experimental configuration [4]. A more detailed review of the range of equipment associated with the DESPEC collaboration for different configurations is available in Ref. [3].

The focus of the current work is on the simulated full-energy peak efficiency response of the FATIMA for the DESPEC experiments at FAIR Phase-0. The simulations were carried out with all components of DESPEC experimental setup in place, including the AIDA and GTC detectors. The simulations were performed using the GEANT4 based [10] modular open source analysis framework NPTool (Nuclear Physics Tool) [11] which offers a unified platform for designing, preparing and analysing complex experiments employing multiple detectors often operating in coincidence mode [12–14]. The simulations of the FATIMA presented in the current work are validated using direct comparison with experimental data taken during the first DESPEC experiment at FAIR Phase-0, which was performed in March 2020 [4,5].

2. Details of the FATIMA geometry at DESPEC

During the March 2020 DESPEC experiment, the FATIMA comprised three concentric rings, each containing twelve individual $LaBr_3$(Ce) detector modules [6]. The front face of each detector was mounted tangential to a sphere around a central focus point. The three rings were situated at angles of 44°, −6°, and −44° with respect to a plane orthogonal to the beam direction [6]. The central ring was offset from 0° to avoid the shadows from detector materials associated with the AIDA signal outputs and mechanics. The distance between centre of the array to the detector faces was kept at ≈ 160 mm. The AIDA active stopper was housed in a thin-walled ≈ 1 mm aluminium box at the centre of the FATIMA. Fig. 1 shows the NPTool simulation geometry used for the DESPEC configuration in the current work. A broad description of the technical design and performance characteristics for the FATIMA in a range of different configurations employed at a number of other experimental facilities can be found in Ref. [6].

3. Simulation of the $I^{\pi} = 8^{+}$, isomeric cascade in ^{96}Pd decay using the FATIMA

The first FAIR-0 experiment to use the DESPEC FATIMA configuration focused on gamma-ray fast-timing measurements in $N \sim Z$ nuclei approaching ^{100}Sn [4,5]. This experiment allowed an in-situ validation of the experimental performance of the FATIMA which could be compared with the NPTool simulations presented in the current work. In the experiment, radioactive ions of interest were produced following the projectile fragmentation of an 850 MeV per nucleon ^{124}Xe primary beam incident on a 4 g/cm^2 thick ^{9}Be target. The reaction products were transported through the GSI fragment separator (FRS) and identified event by event according to their mass (A) to charge (Q) ratio using the standard time of flight, magnetic rigidity and energy loss methodologies outlined in Refs. [15,16]. The fully-stripped (Q = Z) radioactive ions were transported to the final focal plane of the FRS where they were implanted into the AIDA active stopper [8]. The Particle Identification (PID) analysis for those ions transmitted to the final focal plane of the FRS, allowed event-by-event separation and selection by mass of charge (A/Q) and atomic number (Z) as described in Ref. [17]. This procedure was validated by inspecting the mass over charge (A/Q) projections selected on fully-stripped Palladium (Z = 46) ions. The measured A/Q values and associated isobaric separation were tested using discrete-energy, isomer-delayed transitions associated with previously reported isomeric decays associated with ^{94}Pd and ^{96}Pd [3,17–22] as measured in the FATIMA. Further details of the experimental work and fast-timing results from this experiment are available in Refs. [4,5].

Fig. 2a shows the Particle-ID (PID), mass over charge (A/Q) projections gated on fully-stripped Palladium isotopes; these ions were determined to have come to rest in the AIDA active stopper. Fig. 2b–d also shows the isobaric selection resulting from gating selection on coincident, isomer-delayed, discrete-energy transitions associated with ^{96}Pd (106 keV, 684 keV & 1415 keV) [17,23]. For comparison, Fig. 2e shows the analogous A/Q projection but gated on an isomer-delayed transition associated with the ^{94}Pd $I^{\pi} = 14^{+}$ isomeric decay cascade [20]. These PID-projection spectra were subject to background subtractions made by taking a normalised projection gated on energies slightly higher than the discrete energy gating transition. The resulting compton and random background gated-projected PID spectrum was then subtracted channel by channel from the full-energy-peak (FEP) gated PID projections, resulting in the final spectra presented in Fig. 2b–e.

3.1. Experimental determination of the in-situ full-energy peak efficiency for FATIMA

Experimentally derived, in-situ values for the full-energy peak (FEP) efficiency for the FATIMA were determined using the ratios of counts from the discrete-energy gated $\gamma - \gamma$ coincidence projections to the comparable singles intensity as measured during the inaugural DESPEC experiment. These values were calculated using the experimental spectra shown in Fig. 3.

Table 1 lists the number of counts in the Palladium-gated isomer-delayed singles spectra shown in Fig. 3. This information, together with the intensity ratios extracted from the spectra presented in Fig. 2 was used to determine the experimental, in-situ full-energy peak efficiency and the observed isomeric ratios for population of the $I^{\pi} = 8^{+}$ isomer in ^{96}Pd.

This analysis assumes 100% decay feeding in the mutually coincident, four-transition cascade $I^{\pi} = 8^{+} \rightarrow 6^{+} \rightarrow 4^{+} \rightarrow 2^{+} \rightarrow 0^{+}$ in ^{96}Pd, via the emission of the discrete transition energies of 106, 325, 684 and 1415 keV respectively [17,22,23].

For a 100% fed cascade, the total γ-ray detection efficiency can be calculated using the ratio of counts for the coincidence-gated transitions for a defined energy gate and the intensities for these same transitions in the similar PID-gated FATIMA singles spectra (see Fig. 3). Correction for any competing internal conversion decay branch also

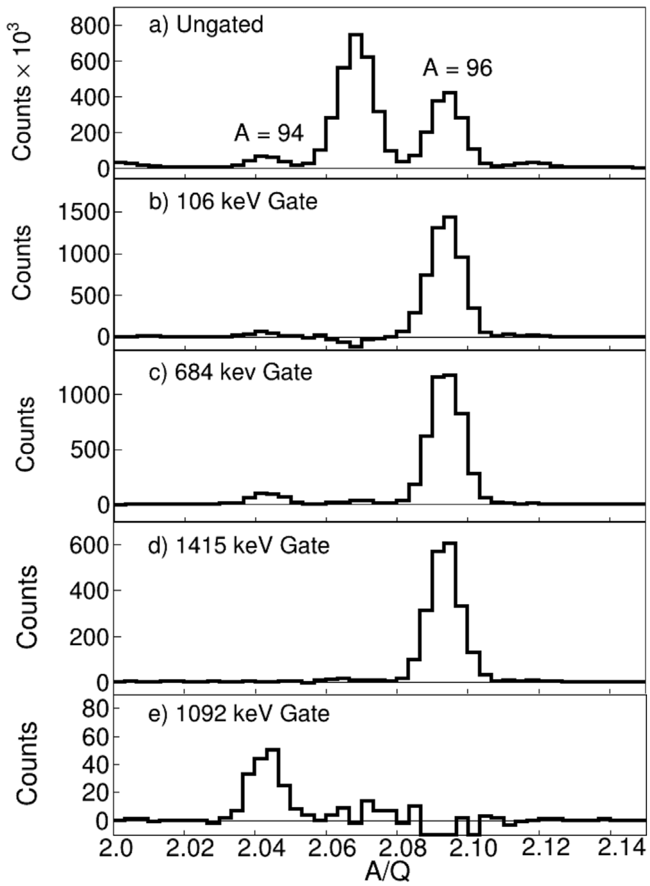

Fig. 2. PID mass over charge (A/Q) projections for fully-stripped palladium isotopes following the projectile fragmentation of a ^{124}Xe beam on a ^{9}Be target. The discrete-energy isomer-delayed gamma rays were measured in a time window of 40 → 400 ns after the ion implantation in the AIDA active stopper. The gamma-ray gated projections shown in (b)–(e) have had normalised random subtractions applied, which are associated with neighbouring, higher-energy (compton background and random) gated projections. Further experimental details can be found in references [4,5].

Table 1
Measured number of counts for PID-gated^{96}Pd ions in coincidence with discrete gamma rays associated with isomeric decays measured in FATIMA between 40 and 400 ns after the implanted ions in the AIDA stopped. These values are taken from the spectra shown in Fig. 2. The total number of transmitted^{96}Pd ions stopped in the centre of the FATIMA associated with this analysis was 1.6 × 10^6.

Transition	FATIMA singles counts
106 keV gated	4180(400)
325 keV gated	6590(250)
684 keV gated	3480(150)
1415 keV gated	1850(100)

needs to be included, leading to a general expression for the experimentally derived FEP efficiency for a transition of energy γ_1 of:

$$\epsilon_{\gamma_1} = \frac{I_{\gamma_1\gamma_2}(1+\alpha_2)}{I_{\gamma_2}} \tag{1}$$

where $I_{\gamma_1\gamma_2}$ and I_{γ_2} are the number of counts in the coincidence gated and singles spectra respectively, and α_2 is the internal conversion coefficient for the gating transition [24] at which energy the FEP efficiency is being calculated. For example, by gating on the 1415 keV, $2^+ \rightarrow 0^+$ transition in the FATIMA coincidence data, the efficiencies of the coincident gamma rays at 106, ($8^+ \rightarrow 6^+$), 324 ($6^+ \rightarrow 4^+$) and

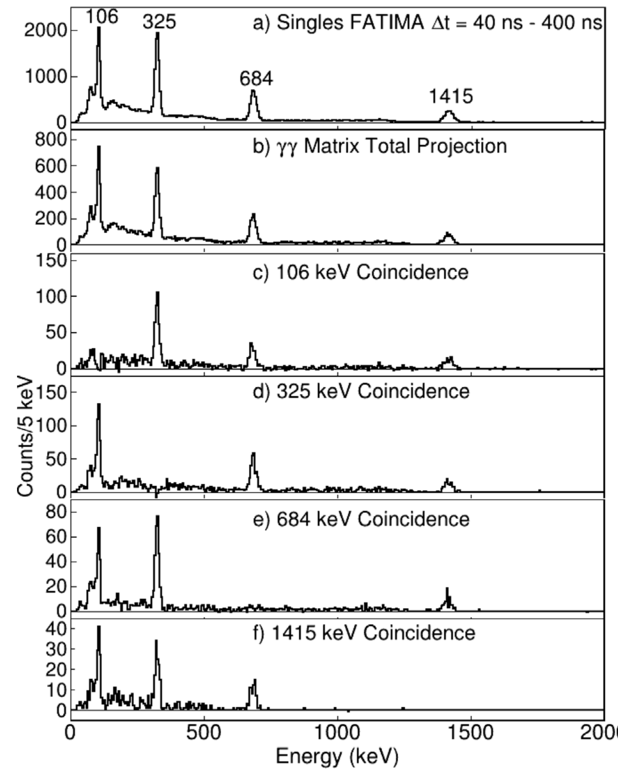

Fig. 3. FATIMA experimental spectra for fully-stripped PID-gated ^{96}Pd ions showing: (a) singles; (b) $\gamma - \gamma$ coincidence total projection; and (c–f) background-subtracted coincidence gates on the 106, 325, 684 and 1415 keV transitions respectively. These spectra all required a clean ^{96}Pd ion to be transmitted to the AIDA stopper and that the emitted gamma rays were measured in a time window from 40 ns to 400 ns after the ion implantation in AIDA.

684 keV ($4^+ \rightarrow 2^+$) were determined using the experimental ratios between number of counts in the spectra shown in the $\gamma - \gamma$ coincidence gates and singles spectra (see Fig. 3). The measured FEP-efficiencies of each of the three transitions projected from the 1415 keV gate provided independent measurements for this energy.

The weighted-mean average taken from the three coincident energies provided the FEP efficiency at that particular gating transition energy. The weighted mean value for the FEP efficiency, ϵ_{wm}, was then calculated using the standard expression,

$$\epsilon_{wm} = \frac{\sum_i w_i \epsilon_i}{\sum_i w_i} \tag{2}$$

where w_i is the weight associated with each individual efficiency data point, ϵ_i and is related to the statistical uncertainty σ_i on each individual data point, by the relation

$$w_i = \frac{1}{\sigma_i^2} \tag{3}$$

The standard error on the weighted mean for the FEP efficiency $\sigma_{\epsilon_{wm}}$ at a particular gating transition energy was determined assuming:

$$\sigma_{\epsilon_{wm}} = \sqrt{\frac{1}{\sum_i w_i}} \tag{4}$$

The current analysis assumes a 100% in-cascade decay sequence with each level decaying 100% by either gamma-ray or internal conversion emission. The correction for the internal conversion branch (which is particularly important for the 106 keV E2 transition in the current work), was accounted for using the tabulated internal coefficients from the BRICC [24] database. This analysis is summarised in the data

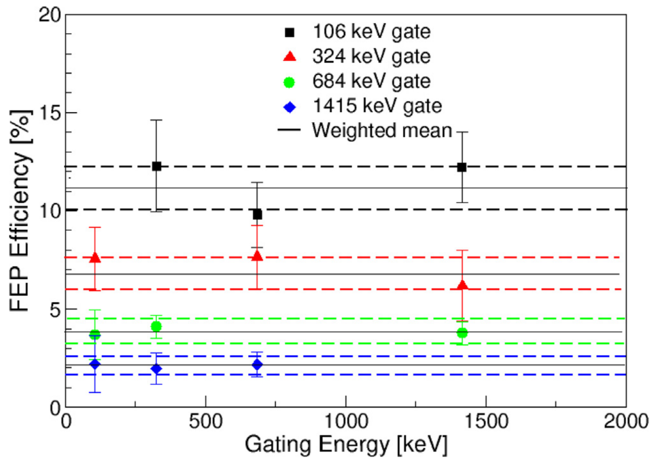

Fig. 4. Weighted mean values for the calculated γ-ray full-energy peak efficiencies for the 106 keV, 324 keV, 684 keV and 1415 keV transitions associated with the decay of the $I^{\pi} = 8^{+}$ isomer in ^{96}Pd. The dashed lines in the figure represent the calculated uncertainties in the weighted-mean averages for each gating transition.

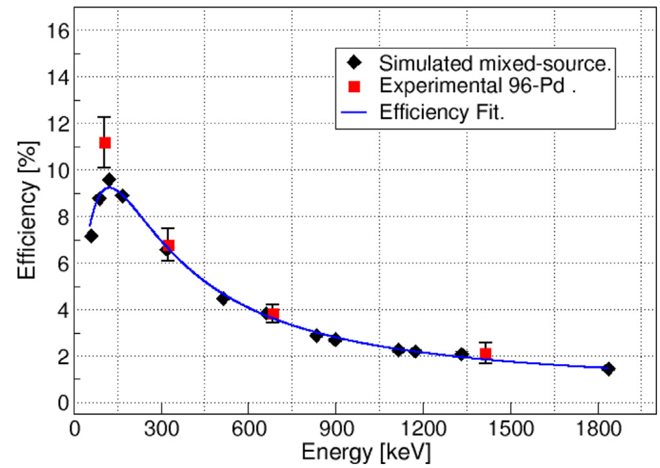

Fig. 5. Full-energy peak (FEP) efficiency response for the FATIMA array determined from the GEANT4 simulations and compared with the experimental, in-situ values calculated for the $I^{\pi} = 8^{+}$ isomeric decay cascade in ^{96}Pd.

presented in Fig. 4, which resulted in values for the FEP efficiencies for the four discrete transitions associated with the ^{96}Pd isomeric cascade of 11.1(11)%, 6.8(7)%, 3.8(6)% and 2.1(5)% at 106, 325, 684 and 1415 keV respectively.

3.2. Simulations to obtain the full-energy peak efficiency for FATIMA

The experimentally-derived FEP efficiencies were compared with the results from the GEANT4-NPTool simulations assuming source positions in the centre of the AIDA active stopper, which corresponds to the geometrical centre of the FATIMA. The FATIMA efficiency response was calculated for 1 million simulated decays of the $I^{\pi} = 8^{+}$ isomer in ^{96}Pd and for a standard NPL mixed γ-ray source with discrete energies ranging from 59.5 keV to 1836 keV and assuming 10^{6} decays of each the following radionuclides: ^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{51}Cr, ^{85}Sr, ^{137}Cs, ^{54}Mn, ^{88}Y, ^{65}Zn and ^{60}Co.

The FEP efficiencies determined from these simulated spectra are summarised in Fig. 5 and compared with the experimentally derived, in-situ values for the ^{96}Pd isomeric cascade. The uncertainties shown for the simulated efficiencies shown in Fig. 5 are taken from the standard error in the number of counts recorded at that energy in the GEANT4 simulations, assuming one million decays for each source radionuclide, which results in the expected Poissonian ($\sigma = \sqrt{N}$) distribution. The assumption of the expected $\sigma = \sqrt{N}$ Poisson-like determination of the uncertainties on the simulated efficiency response was validated by running the simulations for > 50 individual histories using different, initial starting seeds. The resulting MC spectra were then analysing both for the total number of counts and the number of events in individual full-energy peaks and comparing the square root of the mean values in each case with the observed standard deviation for that measured parameter.

3.2.1. Isomeric ratio analysis of the ^{96} Pd $I^{\pi} = 8^{+}$ cascade

The determination of the full-energy peak efficiency allowed a measurement of the isomeric ratio [16,17,21,25,26] for the ^{96}Pd $I^{\pi} = 8^{+}$ state population in the experimental data. This isomeric ratio was then used as an input parameter to estimate the number of isomeric cascades to be simulated in the GEANT4-NPTool modelling to provide a direct spectral comparison between the experimental data and FATIMA simulated response.

The isomeric ratio, R, is defined as [16,17,25]

$$R = \frac{N_{isomer}}{N_{ions}} \tag{5}$$

where N_{isomer} is the total number of ions produced in the isomeric state, N_{ions} is the total number of ions of that nuclear species produced which are transmitted to the focal plane of the FRS and implanted in the AIDA active stopper.

The number of ions measured to be in the isomeric state which decay in the measurement interval at the focal point, N_{isomer}, can be calculated using the expression:

$$N_{isomer} = \frac{N_{\gamma_i}}{\epsilon_i} . \frac{1+\alpha_i}{b_{\gamma}} \times \frac{1}{FG} \tag{6}$$

where N_{γ_i} is the number of discrete γ rays of a fixed energy observed in the decay of the ith decay branch depopulating the isomeric state, ϵ_i is the full-energy peak efficiency of the FATIMA at this discrete energy, b_{γ} is the branching ratio of the γ-ray transition and α_i is the internal conversion coefficient associated with each transition. F and G are correction factors for in-flight losses and the finite measurement respectively where the factor F corrects for the decay of the isomeric state as it travels through the FRS and depends on the Time of Flight (ToF) through the FRS and the corresponding Lorentz factors; G corrects for the finite detection period for the γ decay measurement relative to the isomer half-life [16,17,25].

The correction factors for in-flight losses/decays of the isomeric state between production at the target position and measurements at the focal place can be calculated using the relation:

$$F = exp\left[-\left(\lambda_{q1}\frac{TOF_1}{\gamma_1} + \lambda_{q2}\frac{TOF_2}{\gamma_2}\right)\right] \tag{7}$$

where λ is the decay constant for the nucleus with charge state q and TOF_1 and TOF_2 are the time of flight through the first and second stages of the FRS; λ_{q1} and λ_{q2} are the decay constant for the ion in the charge state $q1$ and $q2$; and γ_1 and γ_2 are the corresponding Lorentz factors [16].

There were 1.6 $\times 10^{6}$, fully-stripped (ie. $q1 = q2 = Z = 46e$) PID-gated ^{96}Pd ions measured at the FRS focal plane over the course of the experiment. Isomeric ratios were calculated using each discrete transition, assuming coincidence requirements for the FATIMA data from the isomeric decay to have occurred between 40 ns and 400 ns after the ion implantation within the AIDA. The final calculated isomeric ratios assumed a time of flight through the FRS for the ^{96}Pd ions of 325 ns, an internal conversion coefficient for the 106 keV $8^{+} \rightarrow 6^{+}$ transition in ^{96}Pd of 1.134(16) [24] and a neutral atomic half-life for the 8^{+} isomer in ^{96}Pd of 1.85(1) μs [3,22].

Based on the measured FEP efficiency values for each of the four discrete γ rays in the cascade decaying from the $I^{\pi} = 8^{+}$ isomer, a

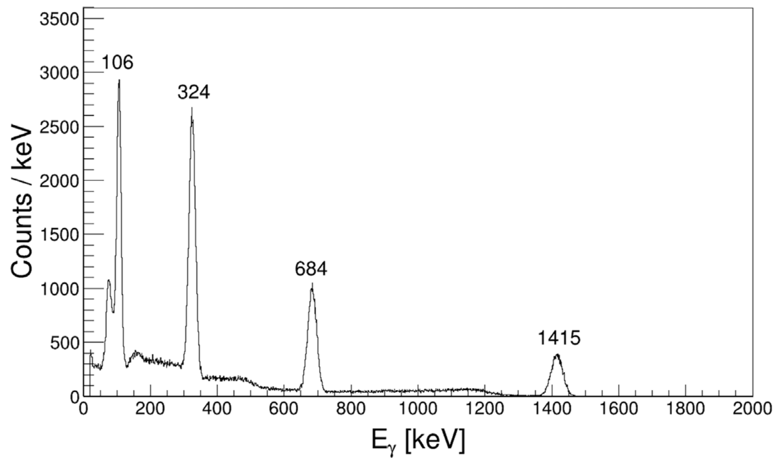

Fig. 6. GEANT4-simulated spectra for FATIMA assuming 10^6 cascades of the $I^\pi = 8^+$ isomeric cascade in ^{96}Pd for a source placed in the centre of the array within the DESPEC configuration.

weighted mean of 50(2)% for the isomeric ratio in ^{96}Pd was determined in the current work. This is comparable with previous measurements of 51(6)% for this isomeric ratio measured at RIBF at RIKEN [21] following the fragmentation of a ^{124}Xe primary beam.

3.3. Direct comparison between experimental and simulated spectra from FATIMA for the isomeric decay in ^{96}Pd

A comparison between experimental and simulated spectra requires input for the energy resolution of the FATIMA as a function of gamma-ray energy. These FATIMA simulations assumed a Poisson-like energy response function, using a random, Gaussian smearing of the instrumental energy resolution response, as outlined in Ref. [27]. The random Gaussian smearing was performed using the measured peak FWHM of the FATIMA as a function of γ-ray energy using the four transitions associated with the ^{96}Pd isomeric decay. This resulted in the expected Poisson-like dependence with a fitted dependence of FWHM = $0.92E^{0.39}$ across the range 106 keV to 1415 keV. Fig. 6 shows the final expected simulated spectra, including the applied Gaussian smearing for the detector resolution response for 1 million simulated decays of the ^{96}Pd $I^\pi = 8^+$ isomer. The side-peak visible next to the 106 keV in Fig. 6 is from characteristic Pb K X rays (74 keV –85 keV) arising from gamma-ray interactions in the 2 mm ring shielding which surrounded each $LaBr_3$ detector to reduce compton scattering events between neighbouring crystals. These X-ray peaks are also clearly observed in the experimental spectra presented in Fig. 3.

The isomeric ratio analysis resulted in an estimate of 97,970 isomeric cascades decaying within the 40 ns and 400 ns post-implantation timing window in the present work and an assumed time of flight through the FRS of 325 ns for the fully-stripped ^{96}Pd isomer. The simulated FATIMA spectra associated with this number of isomeric cascades ions are compared with the experimental γ-ray spectra in Fig. 7.

A slightly higher background level is notable in the experimental data, particularly for energies above the 325 keV FEP. There are most likely due to events in experimental data associated with internal activity radiation from $LaBr_3(Ce)$ crystal, specifically the continuous beta-particle and coincident 789 keV gamma-ray interactions associated with the β^--decay branch of ^{138}La to ^{138}Ba [28]. The effect of the internal activity from the electron capture decay of ^{138}La into the first excited state at 1435 keV in ^{138}Ce is also noted with a small excess of counts in the experimental spectra over the simulations in the singles spectra just above the 1415 keV transition. These differences are effectively removed with the addition of the typical fast-timing coincidence conditions between measured gamma rays ($\Delta T = \pm 40$ ns) in the experimental spectra.

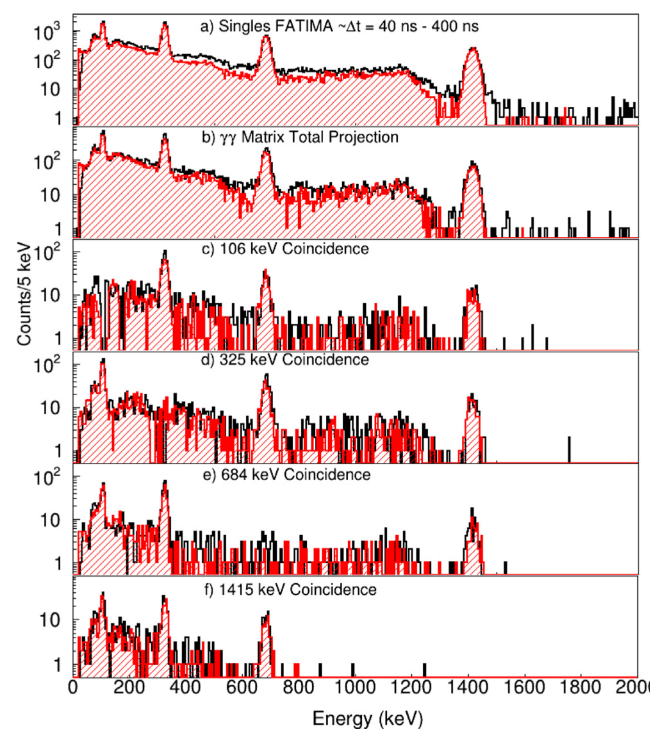

Fig. 7. FATIMA spectra comparing the experimental and simulated (red) decays of the ^{96}Pd isomer for decays between 40 and 400 ns following implantation in the AIDA active stopper. The simulated spectra assume 97,970 isomeric cascades in this timing window period. Fig. (a) singles spectra; (b) total projections for the coincidence matrices. (c) – (f) show the background subtracted coincidence-gated spectra at energies 106, 324, 684 and 1415 keV respectively.

4. Summary

Monte Carlo simulations have been performed for the FATIMA γ-ray spectrometer with the DESPEC setup at FAIR-0. These have been validated by comparison with experimental data using the decay of the $I^\pi = 8^+$ isomer in ^{96}Pd from the first DESPEC experimental campaign a FAIR Phase-0. Experimental Full-energy-peak efficiency values were deduced using the coincidence to singles ratio method. The measured FEP efficiencies at energies 106, 324, 684 and 1415 keV were 11.2(11)%, 6.8(7)%, 3.8(4)% and 2.1(4)% respectively.

CRediT authorship contribution statement

M.M.R. Chishti: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **S. Jazrawi:** Writing – original draft, Investigation, Formal analysis, Formal analysis. **R. Shearman:** Writing – original draft, Methodology, Investigation, Formal analysis. **P.H. Regan:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis. **Zs. Podolyák:** Writing – original draft, Methodology, Investigation, Editing. **S.M. Collins:** Writing – original draft, Methodology, Investigation, Formal analysis. **M. Górska:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis. **B. Cederwall:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **A. Yaneva:** Writing – original draft, Review & editing, Investigation. **G.X. Zhang:** Writing – original draft, Review & editing, Investigation. **J. Cederkall:** Writing – original draft, Review & editing, Investigation. **A. Goasduff:** Writing – original draft, Review & editing, Investigation. **H.M. Albers:** Writing – original draft, Review & editing, Investigation. **S. Alhomaidhi:** Writing – original draft, Review & editing, Investigation. **A. Banerjee:** Writing – original draft, Review & editing, Investigation. **A.M. Bruce:** Writing – original draft, Review & editing, Investigation. **G. Benzoni:** Writing – original draft, Review & editing, Investigation. **B. Das:** Writing – original draft, Review & editing, Investigation. **T. Davinson:** Writing – original draft, Review & editing, Investigation. **L.M. Fraile:** Writing – original draft, Review & editing, Investigation. **J. Gerl:** Writing – original draft, Review & editing, Investigation. **J. Jolie:** Writing – original draft, Review & editing, Investigation. **N. Hubbard:** Writing – original draft, Review & editing, Investigation. **P.R. John:** Writing – original draft, Review & editing, Investigation. **R. Lozeva:** Review & editing, Investigation. **A.K. Mistry:** Writing – original draft, Review & editing, Investigation. **B.S. Nara Singh:** Writing – original draft, Review & editing, Investigation. **M. Mikolajczuk:** Writing – original draft, Review & editing, Investigation. **M. Polettini:** Writing – original draft, Review & editing, Investigation. **N. Pietralla:** Writing – original draft, Review & editing, Investigation. **J.M. Regis:** Writing – original draft, Review & editing, Investigation. **M. Rudigier:** Writing – original draft, Review & editing, Investigation. **E. Sahin:** Writing – original draft, Review & editing, Investigation. **A. Sharma:** Writing – original draft, Review & editing, Investigation. **M. Si:** Investigation. **J. Vesic:** Writing – original draft, Review & editing, Investigation. **V. Werner:** Writing – original draft, Review & editing, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M.M.R. Chishti reports financial support was provided by Science and Technology Facilities Council. P.H. Regan reports financial support was provided by Science and Technology Facilities Council. S. Jazrawi reports financial support was provided by Science and Technology Facilities Council. Zs. Podolyak reports financial support was provided by Science and Technology Facilities Council. R. Shearman reports financial support was provided by UK Government Department for Business, Energy and Industrial Strategy. P.H. Regan reports financial support was provided by UK Government Department for Business, Energy and Industrial Strategy. S.M. Collins reports financial support was provided by UK Government Department of Business, Energy and Industrial Strategy.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.nima.2023.168597.

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