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Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Data acquisition and Python processing using CAEN Digitizer DT5730S for Perturbed Angular Correlation Spectroscopy: the PACIFIC^2 route.

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Abstract: In this Letter of Intent, we propose a series of performance studies on data processing in γ-γ Perturbed Angular Correlation (PAC) spectroscopy, aiming for the substitution of outdated analog processing systems for modern digital ones. We plan to use the DT5730S digitizer from CAEN S.p.A, suited for both 4 and 6-detector PAC configurations setups, alongside the PACIFIC^2 suite—a suite of Python tools designed for streamlined data handling and analysis. We plan to evaluate the performance capabilities of our integrated software and hardware approach, focusing on real-time analysis using short-lived isotopes during PAC experiments on samples implanted with ^{111m}Cd and ^{204m}Pb isotopes.

Summary of requested shifts: ^{111m}Cd: 3 shifts, ^{204m}Pb: 2 shifts (split into 2 runs over 1 year)

1 Motivation: The CAEN DT5730S Digitizer and the PACIFIC² Software.

The γ-γ Perturbed Angular Correlation (PAC) spectroscopy technique has been a staple of ISOLDE Solid state Physics for more than four decades, offering insights into the hyperfine interactions—both Magnetic Dipole and Electric Quadrupole—following the implantation or diffusion of radioactive probes. [1,2] This method's broad applicability allows for the investigation of a wide array of systems, from single-crystal structures and nanoparticle clusters to organic and gaseous molecular systems. [3,4] Its capability to probe physical phenomena at the atomic scale enables the study of structural, magnetic, and orbital phase transitions in solid-state physics, as well as the examination of radioactive nuclei's intrinsic nuclear properties. [4-7]

Historically, ISOLDE's PAC spectroscopy setups have been tethered to analog equipment, some exceeding 30 years in operation, or to digital processing systems that are both costly and bulky. To modernize and streamline our PAC data processing capabilities, we embarked on a series of performance evaluations using the DT5730S digitizer from CAEN S.p.A. [8] Characterized by its 8 input channels, a 500 MS/s sampling rate, and a 14-bit ADC, this compact digitizer seamlessly integrates into both 4 and 6-detector PAC configurations. Notably, it supports space-efficient data storage in ROOT format through its List acquisition mode, where each detected γ-photon is cataloged with time and energy stamps via the digitizer's online pulse processing algorithms. [8,9] Given the challenge of managing and analyzing vast data sets, which can reach up to 100 GB per single measurement, our team is developing the PACIFIC² suite—a collection of Python-based tools designed specifically for PAC spectroscopy data analysis.

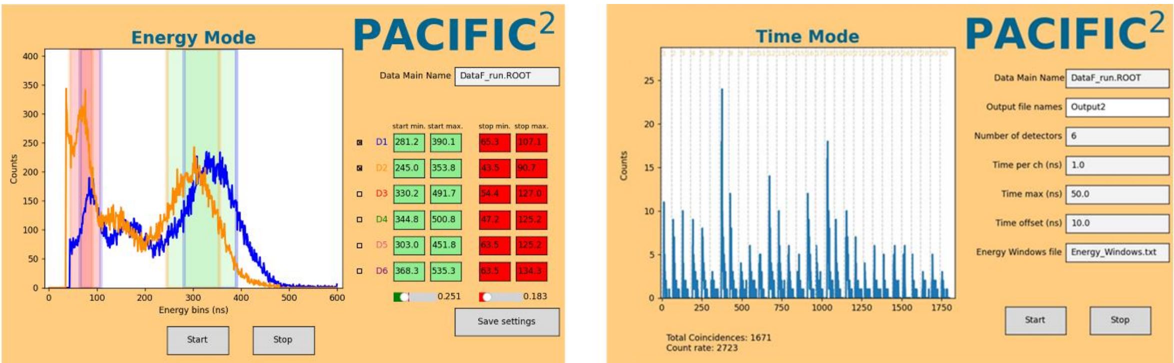

Figure 1: GUI of PACIFIC² for the Energy Window Mode Selection (*left*) and Time mode to obtain Coincidence spectra at 90° and 180° combinations (*right*).

This innovative suite enables efficient filtering and analysis of large-scale data sets to search γ_1-γ_2 coincidence pairs, thereby facilitating the construction of 90°/180°

coincidence spectra, which are fundamental to PAC spectroscopy. [10] The time resolution of the CAEN digitizer was first analyzed by using a ^{22}Na calibration source and a set of two $LaBr_3$ scintillator-based detectors. The detection of pairs of simultaneously emitted γ-photons, with an energy of 511 keV, following positron-electron annihilation processes, was registered. Under optimal conditions, a time resolution of ≈ 360 ps was achieved. This performance is on par with that of the digital systems currently in use. [11]

A preliminary data acquisition test was run during the previous ^{111m}Cd ($T_{1/2}$= 48min) beam time with the DT5730S digitizer connected to a set of 4 BaF_2 scintillator-based detectors. The recently developed PACIFIC² software was used to filter and search the γ_1-γ_2 coincidence pairs of 150-245 keV in post-acquisition mode. Fig. 2 a) shows the respective 90º/180º coincidences spectra obtained for a 44 min acquisition with a sample exhibiting an initial radioactive activity of ≈ 2MBq. The data processing, executed on a contemporary laptop powered by an 11th Gen Intel®CoreTMi7-1165G7@2.80GHz processor, was achieved in less than a quarter of the acquisition time, showing the feasibility of running the Python processing software both in post-acquisition and in real-time conditions while using four-detectors PAC arrays.

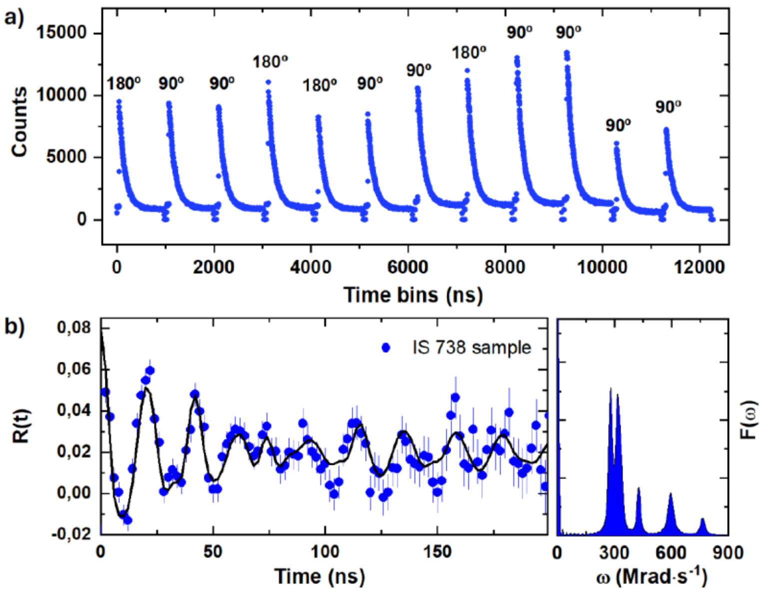

Figure 2: a) Coincidence spectra at 90º and 180º obtained with PACIFIC² processing software from data collected with the DT5730S digitizer during the ^{111m}Cd beam time. b) Respective Perturbation function (R(t)), alongside its mathematical fit, and the Fourier transform of the fit (F(ω)).

Fig. 2 b) shows the PAC observable R(t) function, as obtained by the PACIFIC^2 on a Ca-based Rudlesden-Popper polycrystalline sample studied within the IS738 proposal. As observed in the Fourier transform, the fitted perturbation function accounts for two distinct local environments, agreeing with the results obtained in parallel with currently in-use spectrometers, [11] showcasing the CAEN DT5730S and PACIFIC^2 software's robustness.

2 Methodology: Performance Evaluation tests

The foreseen tests will allow us to evaluate the feasibility of replacing ISOLDE's existing 6-detector analog processing setups with affordable digital alternatives, focusing on comparing data processing speeds with data accumulation rates. We plan to address the sporadic or permanent replacement of two bulky analog systems currently in operation at location 508/R-008:

- The PAC LINE machine, primarily used for high-temperature Perturbed Angular Correlation (PAC) measurements up to 1200 K, has been underutilized due to repeated issues with faulty electronic units. We intend to allocate three ^{111m}Cd shifts, spread over two runs in the next year, to assess its potential permanent replacement by our digital ensemble. This evaluation will include a comparison of PAC functions obtained with the new system against those from the current digital acquisition system, "DIGIPAC" which is also tailored for high-temperature PAC measurements [11].

- The PAC PERM processing unit, as the sole system linked to a functional low-temperature He-closed refrigerator in the 508/R-008 laboratory, supports PAC measurements ranging from 300 K down to approximately 10 K. Traditionally, this setup is dedicated to experiments using ^{111m}Cd or ^{111}In probes. Transitioning to a digital processing system is crucial for expanding our research to include more exotic PAC probes beyond ^{111m}Cd or ^{111}In probe isotopes. A digital system would facilitate rapid modifications to acquisition time settings for the γ_1-γ_2 coincidence evaluation, allowing customization based on the unique lifetimes of different isotopic states. Additionally, it would enable the storage of raw data for post-acquisition analysis, essential when exploring new and exotic γ-cascades. To explore this capability, we plan to dedicate two shifts to ^{204m}Pb experiments.

These tests can run concurrently with the ion-beam implantations scheduled under the active IS730 and IS738 proposals.

Expected Outcomes

These efforts aim to push the processing limits of our current setup while fully leveraging our integrated software and hardware solutions. A successful transition to digital processing, using affordable and compact digitizing systems, would free laboratory space allowing experiments to be more ergonomic, and ensure our operations are no longer susceptible to the unreliability of very old and faulty analog electronics. Instead, we would benefit from immediately analyzable processed data or storing it for post-analysis exploring different gamma-cascade combinations. Furthermore, the compact nature of the Digitizer desktop model, combined with a standard computer, offers unparalleled adaptability to various PAC configurations, supporting both four and six detectors' arrays, being as well adaptable to run the electron-gamma *Kleinheinz – Siegbahn* PAC spectrometer of 508-R-008.

Upon confirming the reliability of the PACIFIC^2 software, its Python-based architecture—set to be released as open source—will serve as a valuable tool for other research institutes. This strategy not only ensures its compatibility with various digital PAC acquisition systems but also promotes collaborative improvements and adaptability across the field.

References

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3 Details for the Technical Advisory Committee

3.1 General information

Describe the setup which will be used for the measurement. If necessary, copy the list for each setup used.

☒ Permanent ISOLDE setup: SSP chamber at the GLM beamline (170/R-026), LINE and PERM 6-cube γ-Detectors (508/R-008), fume-hoods (GLM area 170/R-026 and chemical laboratory 508/R-002), annealing furnaces at 508/R-004.

☐ To be used without any modification

☒ To be modified: LINE and PERM 6-cube γ-Detectors will be swiftly connected to a CAEN DT5730S Digitizer already available at ISOLDE.

☐ Travelling setup (*Contact the ISOLDE physics coordinator with details.*)

☐ Existing setup, used previously at ISOLDE: *Specify name and IS-number(s)*

☐ Existing setup, not yet used at ISOLDE: *Short description*

☐ New setup: *Short description*

3.2 Beam production

- Requested beams:

Isotope	Production yield in focal point of the separator (/μC)	Minimum required rate at experiment (pps)	$t_{1/2}$
^{111m}Cd	1.10^{8} /μC	800E^{10} ppp with equidistant pulses.	49 min
^{204m}Pb	5.10^{7} /μC	800E^{10} ppp	67 min

- Full reference of yield information: target group was consulted.

- Target - ion source combination:

Target molten Sn with VADIS ion source for ^{111m}Cd.

Target UC2 for ^{204m}Pb.

• RILIS?

☐ Special requirements: (*isomer selectivity, LIST, PI-LIST, laser scanning, laser shutter access, etc.*)

• Additional features?

☐Neutron converter: (*for isotopes 1, 2 but not for isotope 3.*)

☐ Other: (*quartz transfer line, gas leak for molecular beams, prototype target, etc.*)

• Expected contaminants: For ^{111m}Cd beam no contaminants are expected, while for ^{204m}Pb beam ^{204}Fr contamination is expected.

• Acceptable level of contaminants: As low as possible.

• Can the experiment accept molecular beams? No.

• Are there any potential synergies (same element/isotope) with other proposals and LOIs that you are aware of? IS713, IS730, IS732, IS738. Our experiment can be scheduled together with these proposals without any issues.

3.3 HIE-ISOLDE

For any inquiries related to this matter, reach out to the ISOLDE machine supervisors (please do not wait until the last minute!).

• HIE ISOLDE Energy: *(MeV/u); (exact energy or acceptable energy range)*

☐ Precise energy determination required

☐ Requires stable beam from REX-EBIS for calibration/setup? *Isotope?*

• REX-EBIS timing

☐Slow extraction

☐ Other timing requests

• Which beam diagnostics are available in the setup?

• What is the vacuum level achievable in your setup?

3.4 Shift breakdown

The beam request only includes the shifts requiring radioactive beam, but, for practical purposes, an overview of all the shifts is requested here. Don't forget to include:

- Isotopes/isomers for which the yield need to be determined

- Shifts requiring stable beam (indicate which isotopes, if important) for setup, calibration, etc. Also include if stable beam from the REX-EBIS is required.

An example can be found below, please adapt to your needs. Copy the table if the beam time request is split over several runs.

Summary of requested shifts:

With protons	Requested shifts
Yield measurement of isotope 1	
Optimization of experimental setup using isotope 2	
Data taking, isotope 1	^{111m}Cd: 3 shifts
Data taking, isotope 2	^{204m}Pb: 2 shifts
Data taking, isotope 3	
Calibration using isotope 4	
Without protons	Requested shifts
Stable beam to GLM	

3.5 Health, Safety and Environmental aspects

3.5.1 Radiation Protection

- If radioactive sources are required:
  - Purpose? Perturbed angular correlation experiments.
  - Isotopic composition? ^{111m}Cd or ^{204m}Pb.
  - Activity? 2.6x10^{6} Bq (^{111m}Cd) or ^{204m}Pb (2x10^{6} Bq).
  - Sealed/unsealed? Unsealed.

- For collections:

– Number of samples? 15

– Activity/atoms implanted per sample? Maximum 2×10^{11} atoms per sample.

– Post-collection activities? Handling, annealing, and PAC measurements at (508/R-008).

3.5.2 Only for traveling setups

- Design and manufacturing

☐ Consists of standard equipment supplied by a manufacturer

☐ CERN/collaboration responsible for the design and/or manufacturing

- Describe the hazards generated by the experiment:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☒	Gas bottles (200 bar – 10 liters) of Argon or Nitrogen for the annealing. Quantity used: 1 cm^3/s during annealing.
	Vacuum	☒	SSP chamber 10^{-6} mbar
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]

Electrical Safety	Electrical equipment and installations	☒	230 V: PERM and LINE spectrometers (508/R-008), SSP chamber at the GLM beam line (170/R-026), fume-hoods (GLM area 170/R-026 and chemical laboratory 508/R-002), annealing furnaces at 508/R-004.

	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☒	Background noise ISOLDE hall and PAC spectrometers
	Working outside normal working hours	☒	Shifts are performed according to the ISOLDE schedule.
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	The samples are transported from building 170 to building 508.
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☒	Annealing up to 850^{o}C
Other hazards			