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# VADER: A novel decay station for actinide spectroscopy

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## ABSTRACT

A research programme focused on the study of the nuclear structure of actinide isotopes has recently been implemented at the IGISOL facility, University of Jyväskylä. Within this scope, a new decay station named VADER (Versatile Actinides DEcay spectRoscopy setup) has been developed and commissioned. The system consists of a compact array of silicon detectors, a liquid-nitrogen-cooled silicon lithium (Si(Li)) detector and three broad energy germanium detectors (BEGe), placed around a thin implantation carbon foil. The combined use of different detectors allows the measurement of $\alpha$ particles, conversion electrons and de-excitation $\gamma$ rays in coincidence, enabling a full reconstruction of nuclear decay schemes. The measurement of basic nuclear decay observables provides a picture of the nuclear shell evolution in neutron-deficient actinides, and highlights the possible emergence of reflection-asymmetric shapes in the region.

## 1. Introduction

Presently, there is a renewed interest in the study of neutron-deficient actinide nuclei due to the evidence for rich nuclear structure phenomena. In particular, in the region north-east of doubly-magic $^{208}$Pb, isotopes of radium, thorium and uranium show evidence for static octupole deformation [1,2]. The strongest octupole correlations leading to the most pronounced reflection-asymmetric shapes are predicted to be found around neutron number $N$=136 and proton number $Z$=88. Recent theoretical efforts have indicated several promising candidates in neutron-deficient isotopes of uranium, plutonium and curium [3]. Nevertheless, there is still a lack of even the most fundamental nuclear ground-state properties in the region, with direct experimental information having been reported for only a few isotopes. Decay spectroscopy provides a window to decay energies ($Q$ values), excited states, spins, parities and other nuclear properties. These properties are essential observables to benchmark theoretical models.

Within this work, the design and commissioning of the novel decay spectroscopy setup VADER (Versatile Actinides DEcay spectRoscopy setup) is reported. VADER has been developed at the Accelerator Laboratory of the University of Jyväskylä (JYFL-ACCLAB), to be used in the low-energy radioactive ion beam branch of the facility, IGISOL (Ion Guide Isotope Separator On Line) [4]. A new research programme has been started with the aim of probing nuclear structure properties of neutron-deficient actinides via laser spectroscopy, mass spectrometry and decay spectroscopy experiments. VADER, focused on nuclear decay spectroscopy experiments, provides a compact and versatile detection system with a low-energy threshold for $\gamma$-ray detection and good electron energy resolution and detection efficiency. The simultaneous detection of $\alpha$ particles, $\gamma$ rays and internal conversion electrons (ICE) can be used to resolve nuclear structure and transition properties.

Similar setups relying on thin implantation foils are in use elsewhere and others are currently under development, e.g., the Windmill device at ISOLDE [5], ASET (Alpha-decay spectroscopy SEtup) and

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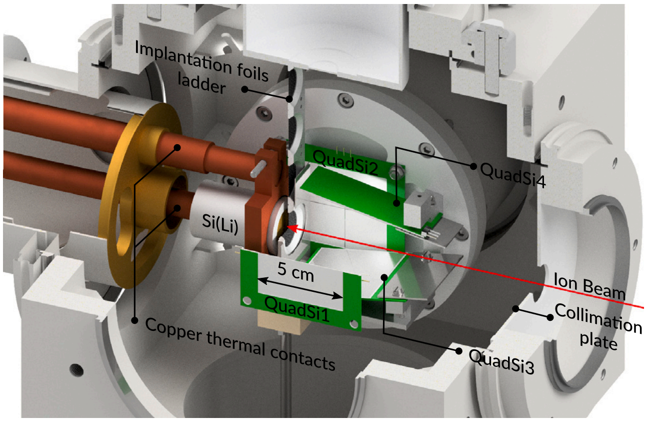

**Fig. 1.** Cross-sectional view of the VADER decay spectroscopy station. The in-vacuum silicon detectors are labelled. Three germanium detectors (not shown) are placed behind the two side flanges that host the segmented quadrant silicon detectors (QuadSi1 and 2), as well as the top flange.

SEASON (Spectroscopy Electron Alpha in Silicon bOx couNter). This feature allows for a coincident detection of $\alpha$ particles and electrons with surrounding silicon detectors. Following the decay of the parent nucleus into its daughter, de-excitation $\gamma$ rays are measured by means of germanium detectors placed in a compact geometry around the implantation foil.

## 2. Experimental setup

The VADER decay spectroscopy setup is presented in Fig. 1, into which a mass-separated radioactive ion beam is directed. The ions are produced via light-ion induced fusion–evaporation reactions in a thin actinide target, e.g., with protons, provided by the local K130 cyclotron with energies up to 65 MeV. The evaporated recoils are thermalized in helium gas in the IGISOL light ion guide, a small volume gas cell, and are extracted through a radiofrequency sextupole electrode towards the mass separator. Here, the particles are accelerated with a 30-kV potential and mass separated by a dipole sector magnet with a resolving power $M/\Delta M \approx 300$, before being delivered to the VADER decay station.

The ions are implanted into a 18 μg/cm$^2$, 18-mm diameter carbon foil facing the incoming beam. Up to four foils can be housed on a moveable ladder. The estimated implantation depth for a 30-kV ion is around 10 nm, which corresponds to a thickness of 2.2 μg/cm$^2$. The $\alpha$ decays of the isotopes of interest can be detected by means of four quadrant silicon (QuadSi) detectors placed in a backward geometry with respect to the beam direction. Two 1-mm thick silicon detectors with four pads, each of 25 mm width, are located on the side flanges of the detection chamber. The remaining two detectors, ∼ 450 − μm thickness with 25-mm pad width, are mounted along the vertical axis with a 10° tilt facing the implantation foil, in order to reduce the $\alpha$ particles' incident angle and to improve the energy resolution and efficiency. Downstream from the implantation foil, at a distance of 4 mm, a 300-mm$^2$ active area and 4 mm thick circular silicon–lithium (Si(Li)) detector is placed to identify the $\alpha$ decays occurring in the forward direction. Thanks to the presence of a copper thermal conduction plate cooled with the use of liquid nitrogen, the detector is able to measure low-energy electrons produced by the internal conversion of the $\alpha$-decay populated excited states. The $\alpha$-particle detection efficiencies for the silicon quadrants and for the Si(Li) detector have been measured using $^{241}$Am and $^{239}$Pu calibration sources to ∼24 % and ∼13 % respectively, resulting in a summed $\alpha$ detection efficiency of ∼37 %. Finally, a set of three germanium (Ge) detectors with composite carbon windows (two Canberra BE6530 and one Canberra BE2020) are placed in a compact geometry around the chamber. A set of holes covered with kapton foils are present on the 2 mm aluminium vacuum separator wall of the germanium detector flanges to increase the detection efficiency of low-energy $\gamma$ rays. The measured energy resolution of the Ge detectors is ∼1 keV (FWHM) at 300 keV with a ∼0.2% detection efficiency at 50 keV. A triggerless data acquisition system has been implemented, composed of two NUTAQ VHS-ADC V4 14-bit 105 MHz cards, synchronized by an externally provided 100 MHz clock. This allows the individual recording and timestamping of all 20 output signals of VADER.

## 3. $^{223}$Ra $\alpha$-recoil source test

VADER has been tested using a $^{223}$Ra $\alpha$-recoil source mounted in a dedicated gas cell in place of the on-line ion guide used during experiments. The source produces $^{219}$Rn ($T_{1/2}$ = 3.96 s) which is extracted, accelerated as a singly-charged ion and implanted into the carbon foil. The decay of $^{219}$Rn into $^{215}$Po ($T_{1/2}$ = 1.78 ms) serves to benchmark the setup.

The acquired decay spectra of $\alpha$ decays, $\gamma$ rays and conversion electrons are highlighted in Fig. 2. A software gate is applied around

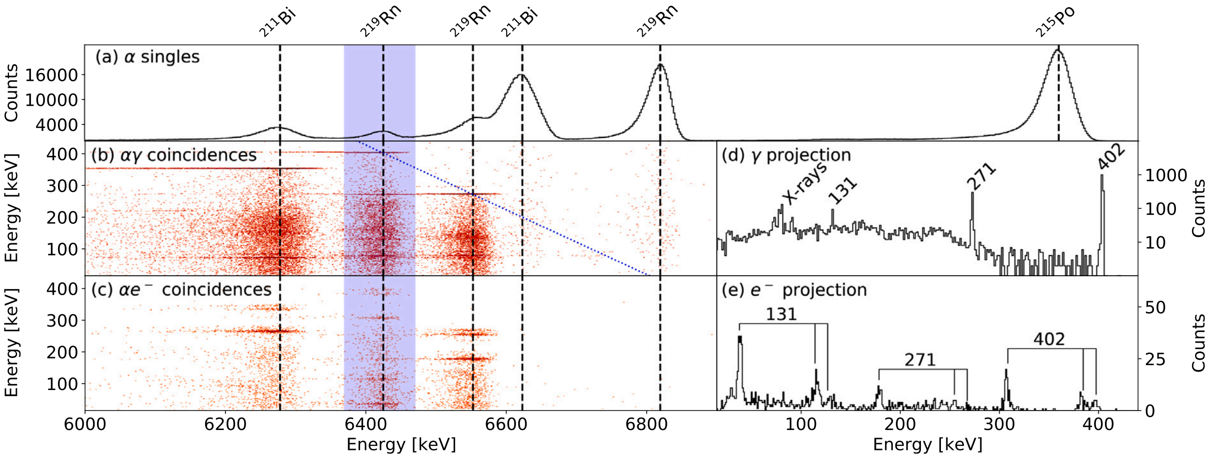

**Fig. 2.** $^{219}$Rn decay chain detected by the VADER decay station. Panel (a) shows the singles $\alpha$ spectrum recorded with the QuadSi detectors at backward angles. Panel (b) presents the coincidence spectrum between detected $\gamma$ rays and $\alpha$ particles. The blue dotted line in panel (b) denotes the $Q_\alpha^* + E_\gamma = Q_\alpha$(g.s.-to-g.s.) of $^{219}$Rn. Panel (c) reports the coincidence spectrum between detected electrons on the Si(Li) at forward angles and $\alpha$ particles. The vertical black dashed lines along the three panels represent the characteristic $\alpha$-decay energies of $^{219}$Rn and its daughter nuclei. The blue shaded area around the 6425-keV $\alpha$ line of $^{219}$Rn indicates the applied software energy gate used to produce the projected spectra on the right (d) and (e) panels. They show, respectively, the gated $\gamma$-ray spectrum with the three lines originating from the 401-keV level of $^{215}$Po, and the corresponding conversion electron spectrum with the K, L and M ICE of each transition marked.

the 6425.0(10)-keV $\alpha$ line from the decay of $^{219}$Rn (blue shaded area) with the resulting coincident spectra of electron and $\gamma$ rays, within a 1-μs delay time, shown in panels d and e. This specific $\alpha$-decay, with a branching ratio of 7.5(6)%, populates the $I^{\pi} = 5/2^{+}$ 401.8-keV excited state in $^{215}$Po. The level can de-excite via a 401.81(1)-keV E2 transition or two consecutive 130.60(3)-keV and 271.23(1)-keV M1+E2 transitions. The de-exciting $\gamma$ lines are indicated in the $\alpha$-gated $\gamma$-ray spectrum (Fig. 2(d)) while the corresponding K, L and M conversion electrons for the three transitions are shown in the $\alpha$-gated spectrum acquired with the Si(Li) detector (Fig. 2(e)). The $\alpha$ resolution measured with the QuadSi detectors varies between 33 keV and 54 keV (FWHM energy resolution at 7 MeV), while the Si(Li) electron resolution from the conversion electron K line at 300 keV is $\sim 3$ keV.

The Si(Li) electron detection efficiency of $\sim 7\%$ has been estimated using the K shell ICE of the 402-keV E2 transition in coincidence with the 6425-keV $\alpha$ line.

## 4. Summary

This work presents an overview of the setup and performance of the new VADER decay station. The use of thin implantation carbon foils is a powerful method to perform decay spectroscopy studies with on-line-produced $\alpha$-emitting nuclei, allowing the coincident measurement of conversion electrons, $\gamma$ rays and $\alpha$ particles without significant summing effects. The use of a cryogenically cooled Si(Li) detector in a compact geometry with the implantation foil ensures an excellent efficiency and energy resolution for conversion electrons, necessary to distinguish the different subshells involved in the conversion process. In addition, the use of kapton-covered apertures on the flanges facing the germanium detectors ensures an increased low energy $\gamma$-ray detection efficiency, a desirable characteristic when studying nuclei with a high density of states close to the nuclear ground state. VADER offers access to the different decay radiations, critical to the full reconstruction of the level schemes. A systematic study of isotopic chains in the neutron-deficient actinide region using VADER is underway, allowing for the observation of nuclear shell evolution and the emergence of collective behaviour.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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