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Short Communication

Monitoring of the radioactivity in the marine environment: a White Paper - Part I

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Abstract

Radioactivity in the marine environment, although present since the Earth's formation, is comparatively understudied in contrast to aerial and terrestrial environments. A thorough examination of the radioactivity levels in aquatic environments can establish a robust foundation for comprehending various geochemical processes and phenomena within the water column and near the seabed, and as a result estimate the impact of radioactivity on local ecosystems. To achieve this objective, *in-situ*, long-term, and continuous monitoring is required. The present part I of the white paper highlights the fundamentals of marine radioactivity, describes the main objectives of an ambitious EU-funded project (RAMONES: Radioactivity Monitoring in Ocean Ecosystems) and introduces the innovative aspects of the technology developed as novel solutions to open problems.

Keywords

marine radioactivity, radioactivity monitoring, innovative technology, ocean ecosystems, spectroscopy

Introduction

The environmental aspects of radioactivity are well known to the scientific community but have also been disseminated to the general public mainly via the broad impact of nuclear weapons use and nuclear disasters on the environment and the human population, such as the bombing of Hiroshima, the nuclear accident of Chernobyl, and the tsunami-triggered Fukushima disaster. Environmental radioactivity, and especially the naturally occurring radioactive materials (NORM) has been present on Earth since the very first moments of its formation as a planet in the solar system. Long-lived isotopes have shaped the conditions on our planet and to a large extent continue to impact our civilization.

One of the principal ecosystem components is the oceans, covering approximately 75% of the surface of the Earth. Marine radioactivity is the part of both natural and anthropogenic radioactivity -the latter introduced into the oceans after 1944 when the first underwater nuclear weapon tests started- that exists in the vast ocean volume, both in the water column and the seabed. Despite marine radioactivity is a key component of the ecosystem, the harsh conditions and the remoteness of the oceans have impeded its detailed and persistent investigation over the years.

As technological advancements have allowed for deeper exploration of the oceans and new sensors have become available to operate in the harsh deep-sea conditions, marine radioactivity has started gaining pace as a means to understand its direct impact on the environment, but also as a proxy to understand large-scale phenomena and human marine activities, such as ocean currents, geotechnics, climate change, costal and seabed drilling, ocean waste and more.

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As part of an EU-funded research portfolio, called Environmental Intelligence, the H2020 EIC Pathfinder project RAMONES (RAdioactivity Monitoring in OceaN EcoSystems; https://www.ramones-project.eu) aims to close the technological gap between the actual need in monitoring marine radioactivity across large spatial and temporal scales and the existing solutions in instrumentation. The present White Paper is split into two parts: Part I, which is the present document, reviews the basic knowledge and terminology related to marine radioactivity, describes the main objectives behind marine radioactivity research and describes the radiation spectrometers developed by RAMONES. Part II, which will follow, will focus mostly on the targeted applications which can benefit from radioactivity measurements in the marine environment, along with the lessons learned during RAMONES development and testing of novel, beyond-the-state-of-the-art instrumentation to monitor marine radioactivity.

The Basics

The Atom

The atom serves as the fundamental unit of chemical elements and it consists of a positively charged nucleus that is surrounded by an assembly of electrons which are negatively charged, bound together by electrostatic forces. The vast majority of an atom's mass resides within its nucleus, while the electron cloud makes only a very small contribution (see a schematic representation in Fig. 1).

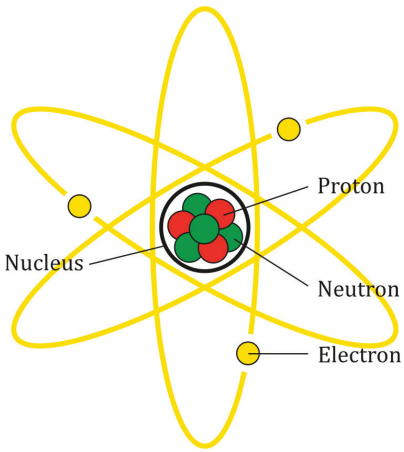

Figure 1. A schematic representation of the structure of the atom (image from Wikipedia 2024).

The Atomic Nucleus

The atomic nucleus consists of protons and neutrons, cumulatively called nucleons, and is positively charged since the protons have a positive charge and neutrons are neutral. Protons and neutrons are held together by the strong nuclear force, which is an attractive force at distances between 0.4 and 3 femtometers keeping them stable. For distances less than 0.4 femtometers the nuclear force is repulsive, not allowing the protons and neutrons to collapse and implode in on themselves. Each atom is unique in its elemental identity, distinguished by the specific number of protons within its nucleus. Every element is characterized by its specific number of protons, neutrons, and electrons. While the atoms within a given chemical element uniformly exhibit an identical number of protons and electrons, the critical distinction lies in the variable quantity of neutrons. Isotopes refer to atoms possessing an identical proton count yet featuring diverse neutron numbers. Although these isotopes nearly mirror each other's chemical characteristics, their differing masses result in distinctive physical properties.

Unstable nuclei

The behavior of particles within the atomic nuclei is described by quantum wave functions, which represent the probability distribution of finding a particle in a particular state. The stability of atomic nuclei is governed by the balance between the forces that bind protons and neutrons together and the repulsive forces between positively charged protons. Within a nucleus, the strong nuclear force, which is attractive in very short distances, binds protons and neutrons together. However, the electromagnetic force, which is repulsive and acts between positively charged protons, tries to push them apart. The energy required to separate the nucleons (protons and neutrons) is called binding energy of the nucleus. In stable nuclei, the binding energy per nucleon is maximized compared to unstable nuclei which is lower, indicating that the nucleus is less tightly bound, and it may undergo radioactive decay to transit into a more stable configuration.

When a nucleus undergoes radioactive decay, it releases energy in the form of various particles (such as alpha or beta) or electromagnetic radiation. This released energy has a corresponding mass in accordance to Einstein's equation $E=mc^2$. If we compare the mass of the original nucleus before decay and the mass of the products after decay, the latter is slightly less. This difference in mass is known as mass deficit and it occurs due to a part of the original mass of the nucleus being converted into energy during the decay process. This energy is carried away by the emitted particles or radiation. Thus, mass and energy are two sides of the same coin, and they can be converted into each other under certain conditions such as those encountered during radioactive decay.

What is radioactivity?

Radioactivity refers to the process by which unstable atomic nuclei undergo spontaneous transformation, emitting radiation in the form of particles or electromagnetic waves. This phenomenon occurs when the nucleus of an atom is not in a stable configuration, typically due to an excess of protons or neutrons. As the nucleus seeks a more stable state, it emits radiation, a process known as radioactive decay.

Radioactive elements have been an integral part of our planet since its formation. Naturally occurring radioactive materials are found in the Earth's crust, as well as in the walls and floors of our homes, schools, offices, and even in the food and beverages we consume. Radioactive traces are present not only in the air we breathe but also in our own bodies, including muscles, bones, and tissues, which contain naturally occurring radioactive elements.

Humans have always been exposed to natural radiation originating from both within and outside the Earth. The radiation received from outer space is referred to as cosmic radiation or cosmic rays. In addition to natural sources, humans are exposed to man-made radiation, such as X-rays used for medical diagnostics and cancer therapy. Fallout from nuclear explosives testing and the release of small quantities of radioactive materials from coal and nuclear power plants also contribute to human radiation exposure.

Most atoms on Earth are stable due to a balanced and steady arrangement of particles (protons and neutrons) in their nucleus. However, there are atoms which face difficulty in retaining these particles together and as a result they undergo spontaneous transformation into more relaxed states while simultaneously releasing energy in the form of radiation (waves or particles) to shift to a more stable configuration. This physical process is known as radioactivity, and the disintegrating nuclei are referred to as radioactive nuclei. The rate of radioactive decay is measured in units called becquerels, where one becquerel equals to one decay per second.

Radioactive elements undergo decay at varying rates, measured in terms of half-lives, unaffected though by external factors like temperature or pressure. The half-life represents the time required for half of a given quantity of a radioactive element to disintegrate. The longest half-life belongs to Uranium-238, found globally in varying amounts, lasting 4.5 billion years. Other isotopes exhibit half-lives ranging from years to less than a millionth of a second, including durations of months, days, minutes, and seconds (IAEA 2024). For instance, Potassium-40, which is a primary source of radioactivity in our bodies, has a half-life of 1.42 billion years.

Natural and artificial radioactivity

Radiation can be either natural or man-made. The latter is called artificial. Natural radioactivity has been present since the Earth's formation and it comes mainly from four sources. The first one is cosmic radiation which originates from the sun and stars. Then it follows the ambient air which gives off radon, a radioactive gas which emanates from the decay of uranium within the Earth's crust. The third one is terrestrial radiation since radioactive materials exist naturally in soil and rocks.

Finally, the source of natural radioactivity is the internal radiation which comes from foods and drinks that humans consume. Both possess radioactive elements that, upon ingestion, are in equilibrium with the non-radioactive natural isotopes which also exist in our organism. These elements, crucial for life, include radioactive isotopes like potassium-40 (^{40}K) or carbon-14 (^{14}C). Natural radioactivity has no observable impact, causing no visible harm to health. Due to evolutionary pathways of millennia, the body naturally integrates it as a component of the biological process.

A series of radioactive decay events which occur when the disintegration of one radioactive element produces a new element, which may also be radioactive, is called decay chain. The natural decay chains are four in total. The decay chain depicts a succession of radioactive decay events involving various radioactive decay products, unfolding as a sequential sequence of transformations. In the typical scenario, a radioisotope doesn't undergo direct decay to a stable state; instead, it transitions to another radioisotope. Consequently, a sequence of decay steps ensues until the atom achieves stability, signifying that its nucleus has reached a state of equilibrium. Among the fourth chains, the most abundant are uranium-238 (^{238}U) and thorium-232 (^{232}Th) which are illustrated in Fig. 2. In the quantities of natural uranium that we find in our solar system, there is a relative content of 0.7% of the isotope Uranium-235 (^{235}U), which is the parent nucleus of the third natural chain, while Neptunium-237 (^{237}Np) is the parent nucleus of the fourth chain, where some radionuclides can be used for examinations (X-rays) or medical treatment (radiotherapy) and industrial products where radionuclides are produced in nuclear installations and mining.

In contrast to natural radioactivity, the artificial one occurs due to human intervention. The two main sources of artificial exposure are the civilian and military nuclear programs. The former encompasses a range of activities, including nuclear power generation and the use of radioactive materials in medical and industrial applications for peaceful purposes. The latter includes nuclear-weapon production and testing in the atmosphere as well as underground or at the marine environment.

Types of radiation

The term radiation is very broad and can be characterized as either non-ionizing or ionizing depending on the energy of the radiated particles as illustrated in Fig. 3. The former type of radiation is lower energy radiation that is not able to completely remove an electron from an atom or molecule whether in matter or living organism. However, its energy can make the molecules vibrate and produce heat and this is for instance the working principle of microwave. On the other hand, the ionizing radiation possesses sufficient energy to detach an electron from an atom or molecule and break chemical bonds. If these productive ions, which are atoms or molecules that have lost or gained one or more electrons, interact with living tissues, they can affect normal biological processes in them. With the correct use, this kind of radiation may be beneficent for humans such as with the X-ray machines in medical diagnostics

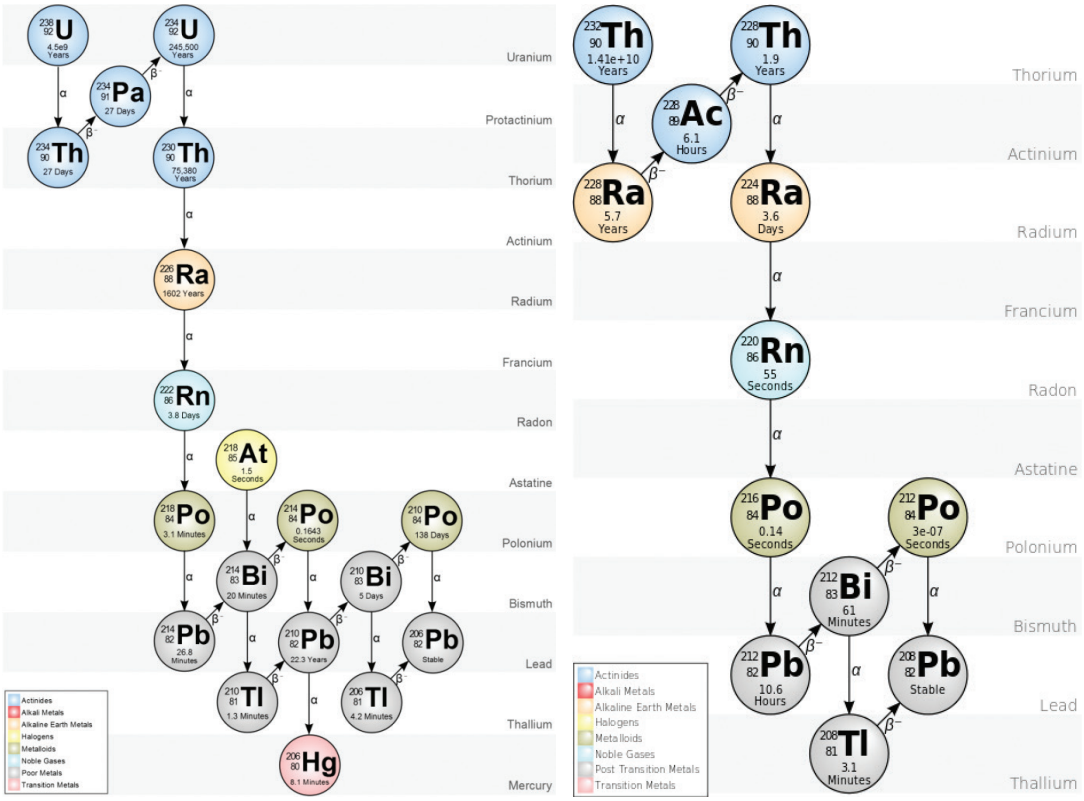

Figure 2. Schematic representation of the natural decay chains of the long-lived natural isotopes (left) Uranium-238 and (right) Thorium-232. Vertical decays correspond to alpha radiation, while diagonal decays correspond to beta radiation (Wikipedia 2024).

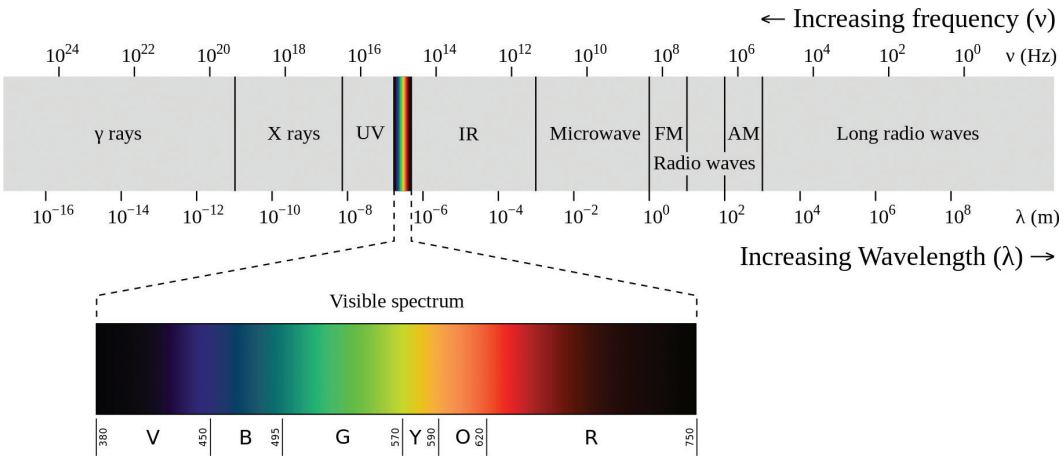

Figure 3. Different types of radiation (Wikipedia 2024).

Different forms of radioactive decay resulting in ionizing radiation arise from the type of particles or waves released by the nucleus to attain stability. The commonly discussed forms of ionizing radiation include (Krane 1988):

- Alpha radiation in which the decaying nuclei release heavy, positively charged particles, called alpha particles that have two protons and two neutrons in their nucleus. Atoms possessing radioactive nuclei with too large proton to neutron ratio frequently emit alpha particles as observed in the case of ^{238}U in Fig. 4. A sheet of paper or the thin outer layer of our skin (epidermis) are sufficient to completely block alpha radiation as depicted in Fig. 5. However, when materials emitting alpha particles may be introduced into the body through inhalation, or ingestion, and have the potential to directly expose internal tissues, leading to biological harm.
- Beta radiation in which electrons are released from the nuclei. The fundamental process in beta decay involves the transformation of a proton into a neutron by the emission of a positron or conversely a neutron into a proton by the emission of an electron. The beta particles (electrons or positrons) are more penetrating than alpha and can pass through 1–2 cm of water. Beta radiation can be effectively halted by a few mm-thick sheet of aluminum.

- Gamma rays are electromagnetic radiation similar to visible light or radio waves but with higher energy. This form of radiation commonly succeeds alpha or beta disintegration. Following the emission of an alpha or beta particle, the daughter nuclei are found in excited states, as their nucleons are not yet in equilibrium. Subsequently, the excess energy is promptly released through the emission of gamma radiation (photons), known as gamma radioactivity. An illustration of this process is seen in Fig. 4 when cobalt-60 (^{60}Co) is transformed through beta disintegration into nickel-60 (^{60}Ni). To achieve a stable state, ^{60}Ni emits gamma radiation. Gamma rays can be stopped by thick walls of concrete or lead.

Even though we may not perceive or sense the existence of radiation, it can be identified and quantified in extremely small amounts using straightforward radiation measuring instruments as it will be discussed later.

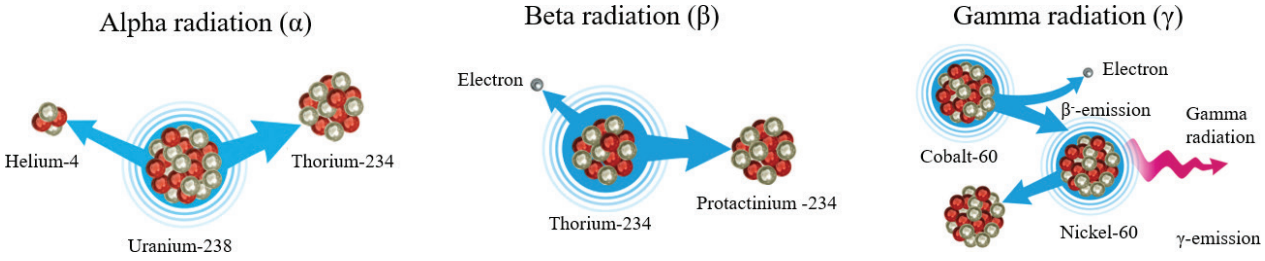

Figure 4. Some of the types of ionizing radiation. The numbers near the name of the elements refers to the total number of protons and neutron in their nucleus (CEA 2014).

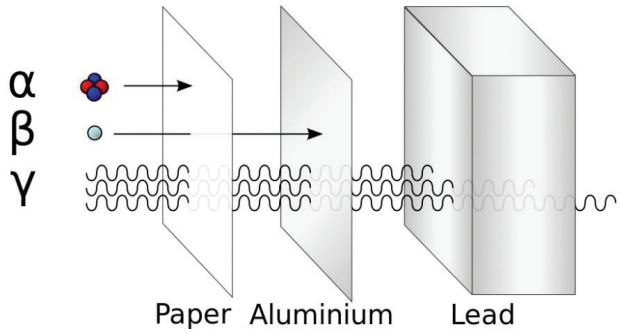

Figure 5. Depiction of the varying penetration capabilities of three distinct types of radiation through solid substances. Alpha particles (α) are effectively halted by a sheet of paper, beta particles (β) are stopped by an aluminum (Al) plate, and gamma radiation (γ) is damped when it penetrates lead (Pb) (Wikipedia 2024).

Radioactivity in the marine environment

Natural radioactivity is present in both seawater and ocean sediment as on land and in the atmosphere since the Earth's formation. On the other hand, the artificially produced radionuclides have entered the marine environment, either stemming from military activities, industrial emissions, medical procedures or nuclear accidents with the arrival of nuclear technology in the late 1940s. The radionuclides of concern included the enduring plutonium (Pu), americium (Am), cesium (Cs), and strontium (Sr), which are byproducts of nuclear explosions. Even though the test-ban agreement of 1963, which was signed by the United States, Great Britain, and the Soviet Union, prohibited nuclear weapon tests or any other nuclear explosion in the atmosphere, underwater, and in outer space, there are other sources that can release man-made radionuclides into the ocean and in the atmosphere. These can be low-level liquid discharges from reprocessing plants, large-scale releases due to natural disasters (e.g., Fukushima Dai-Chi reactors in 2011), as well as smaller-scale radiological events (e.g., nuclear vessel wrecks or marine disposal of nuclear material) (Vives i Batlle 2012).

A clear distinction exists between naturally occurring radioactive materials (NORM) and anthropogenic radioactivity. Naturally occurring radionuclides result from the Earth's intricate physical, chemical, and transport mechanisms, with a significant accumulation occurring in the rocks and sediments that form the Earth's crust and ocean basins. NORM primarily encompass isotopic chains originating from long-lived uranium and thorium isotopes, presenting a low but persistent risk for the ecosystems. Anthropogenic radioactivity is predominantly linked to unstable isotopes generated by human activities, including medical radioisotopes and nuclear power plant waste treatment. Technological activities like mining can further elevate NORM concentrations in the environment, leading to Technologically Enhanced NORM (TENORM) that pose notable public health risks. However, monitoring of TENORM remains insufficient globally, largely confined to specific sites. Directives from international bodies, such as the EU Radiation Safety Commission and IAEA, emphasize the crucial necessity for continuous monitoring to comprehend the environmental repercussions.

Seawater radioactivity exhibits geographical uniformity and is primarily influenced by ^{40}K, a naturally occurring isotope. In contrast, radiation levels in sediment vary depending on the sediment type and location. Man-made radionuclides which contribute to natural radioactivity in the marine environment, can find their way into the marine environment through various pathways, including direct discharges, atmospheric deposition, and run-off from land.

Studying how radionuclides are distributed in the ocean is important for several reasons. Primarily, understanding the destiny of radionuclides is essential for evaluating potential environmental or human health implications.

This knowledge is also essential for quickly assessing the impact of accidental releases, like those from nuclear facilities, waste sites, or the transport of high-level waste in the ocean. Radionuclides also act as useful tracers, providing important insights into various marine processes. Due to the relatively well-defined temporal and spatial characteristics of radionuclide introduction into the ocean, their movement within the ocean unveils valuable information about numerous processes in the water column, as well as in biological and sedimentary systems (Livingston and Povinec 2000).

Radiation detection in the marine environment

Generally, the radioactivity of a sample can be determined by counting the number of atoms undergoing spontaneous decay per second. Specially designed instruments are employed to detect the specific type of radiation emitted during each instance of decay.

Despite advancements in technology, the sampling, measurement and study of radioactivity in the marine environment continue to face significant gaps in coverage. Current instrumentation offers limited monitoring capabilities for both short and long-term periods, primarily concentrating on studies near the ocean surface. The methods and tools utilized in marine radioactivity monitoring are largely adaptations of those developed for land and air studies which are incompatible in the majority of cases due to the harsh conditions of the marine environment. The International Atomic Energy Agency (IAEA) has developed a database and information system called Marine Radioactivity Information System (MARIS) which collects and compiles data of marine radioactivity, including measurements of radionuclides in seawater, sediments, marine organisms, and other components of the marine environment. Notwithstanding the existence of MARIS which serves as a centralized repository for information related to the monitoring and assessment of marine radioactivity worldwide and that can be globally used among scientists and policymakers, there persists a substantial gap when compared to the extensive measurements conducted for land and air radioactivity.

The vast volume of the ocean serves as a protective barrier, shielding the human population from sources of radioactivity deep within the water, whether of natural or man-made origin. Oceans are frequently linked to natural resources or intense phenomena that may be associated with natural radiation, such as earthquakes. It is known that active seismic faults are related to radioactive radon emanation through cracks and fractures of the crust, which typically becomes earlier than earthquake events. However, the awareness of radioactivity in marine environments is often overlooked in terms of potential environmental and human health risks. For that reason, current guidelines from global organizations, including the EU Radiation Safety Commission and IAEA, emphasize the significance of ongoing monitoring to comprehensively grasp the environmental implications (IAEA 1985; European Commission 2003)

Detecting radioactivity in the marine environment faces inherent challenges due to the slow progress in developing sensor technology specifically designed for marine use. The harsh conditions of the oceans impose significant constraints on achieving long-term, continuous, and flexible radiation monitoring. Additionally, the distance one may detect radioactivity is considerably shorter in water compared to air, introducing further limitations to efficient measurements conducted within aqueous environments such as lagoons, rivers, and basins.

Over the years, many efforts have proposed different solutions for the monitoring of marine radioactivity using various types of instruments and approaches. One common approach involves using NaI(Tl) scintillators (Jones 1989; Tsabaris et al. 2008; Toyoda et al. 2015; Naumenko et al. 2018; Zhang et al. 2018; Byun et al. 2020; Cao et al. 2020). The scintillation crystal material consists of sodium iodide and a bit of thallium and has good detection properties of gamma radiation, but instruments featuring such crystals often present low energy resolution. Energy resolution refers to the ability of a detection system to distinguish between different energies of incoming radiation. Higher energy resolution allows for more accurate and precise measurements, as well as more detailed information about the radiation sources being detected. To address this, researchers have explored other types pf scintillators, such as $LaBr_3$(Ce) (Su et al. 2011; Zeng et al. 2017; Dou et al. 2021) and $CeBr_3$ (Tsabaris et al. 2019), which generally offer better resolution than NaI(Tl). However, these detectors may have issues due to intrinsic radioactivity, i.e. their own crystal emits radiation spontaneously, contributing to the overall radioactivity coming from an external source. This makes the identification of the radioactivity hotspots in low-counting rate environments, such as the oceanic environment, very challenging. Another issue is their large size, which adds technical difficulties in their deployment in the marine environment. Lee and collaborators (Lee et al. 2023) explored alternative approaches, including the use of a CsI(Tl) scintillator paired with a silicon PIN diode, and in another attempt, a GAGG(Ce) crystal coupled with a SiPM (Lee et al. 2020). Both studies encountered challenges with poor energy resolution. From another point of view, the need for measurements with higher energy resolution led a group of researchers (Povinec et al. 1996) to deploy an HPGe detector specially designed for marine environment studies, coupled with a NaI(Tl) scintillator. While HPGe semiconducting crystals offer high-energy resolution, the requirement for continuous cooling -typically with liquid nitrogen (LN2)- to reach low temperatures (-196 °C) limits the duration of unsupervised monitoring in the ocean, particularly in deep depths.

A novel approach of the ocean's radioactivity monitoring

As mentioned in the Introduction, a H2020 EU Pathfinder Programme, called RAMONES (RAdioactivity Monitoring in OceaN EcoSystems), has focused on undertaking some of the above issues and limitations, being ambitious in establishing new standards in radioactivity monitoring in the marine environment, while developing methodologies based on existing state-of-the-art (SoA) interdisciplinary approaches and benefiting from the latest advances in marine technology. To this end, a wide set of novel submarine radiation-sensing instruments are being developed for *in-situ*, continuous and long-term monitoring of natural and artificial radioactivity in harsh subsea environments providing both high detection efficiency and fine resolution. SoA sensors and methods will be developed and cross-combined to create a novel, currently non-existing, generation of low-power and fast integration-time underwater instruments for radiation measurements in extreme oceanic locations. Deployed on SoA low-power, long-endurance glider-type autonomous underwater and surface vehicles, RAMONES will enable rapid deployment, with dense spatial and temporal surveys over large areas for extended periods of time. With near real-time and *in-situ* measurements, RAMONES aims to provide real-time assessment of environmental risks, facilitating prompt response for risk mitigation (humans, environment).

The RAMONES fleet of instruments will equip a stationary benthic laboratory to operate in deep waters (up to 500 m). All the instruments will be encapsulated in appropriate housings to resist high pressures, corrosion and seawater forces offering accurate measurements. Some of the housings specifications, such as the material and thickness, were provided by detailed simulations. Apart from the housing materials, energy consumption stands out as a crucial consideration in the marinization of battery-operated autonomous systems. The development of low-power electronics and innovative power management techniques plays a key role in maximizing the operational endurance of these systems.

One of the instruments RAMONES is offering for detecting gamma radiation is GASPAR (Gamma Spectrometer for Marine Radioactivity Studies) with an electromechanically cooled HPGe crystal. It will equip the stationary benthic lab and it is aimed to conducting high-resolution, *in-situ* γ spectroscopy. The primary innovation of the instrument lies in the integration of electromechanically assisted thermoelectric cells to abduct heat, ultra-cooling (77K) the Ge crystal to function efficiently as a radiation sensor, eliminating the necessity for a continuous supply of liquid nitrogen as it is required for standard HPGe detectors. This technology has only recently entered the commercial domain and is progressively becoming accessible for nuclear physics experimental installations (Lozeva et al. 2019). For underwater studies, this kind of technology will be used for the first time and GASPAR will set a new standard for marine applications as the first in a generation of HPGe detectors designed for portability, smaller size, and significantly increased operational duration. A picture of the instrument is depicted in Fig. 6.

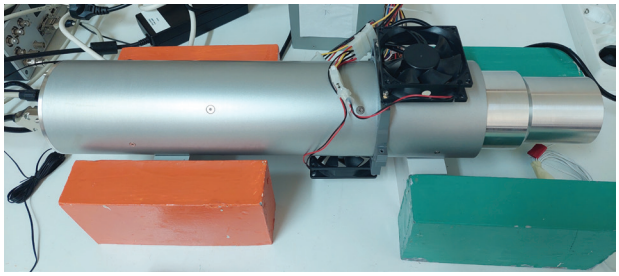

Figure 6. The electromechanically cooled HPGe detector (GASPAR) during testing on the lab bench.

Another class of radiation instruments RAMONES will develop and deploy are the γ-sniffers. These are mobile, lightweight γ-ray spectrometers enclosed in suitable housing, integrated into autonomous underwater gliders (AUG). Each γ-sniffer is designed to conduct extended surveys, covering substantial water volumes over extended periods, to spot increased levels of radioactivity. The spectrometers will feature semiconductive CdZnTe (CZT) crystals, known for their high atomic number and density, resulting in excellent detection efficiency (Del Sordo et al. 2009). Additionally, CZT detectors offer good energy resolution, portability, low power consumption, and their crystals do not produce intrinsic radioactivity. While CZT detectors have undergone recent testing for radioactivity measurements in the South China Sea (Zhou et al. 2022), the present study focuses on innovative instruments set to be deployed for the first time in European waters. This kind of sensors are depicted in Fig. 7.

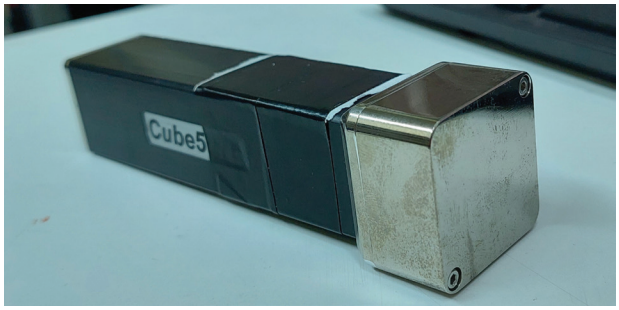

Figure 7. A CZT crystal (central part of the RAMONES γ-Sniffers).

Apart from the detection of gamma radiation, RAMONES is developing a novel spectrometer for monitoring radon concentrations through spectroscopy in the marine environment. The natural radioactive decay chains primarily progress through alpha decay, releasing energetic helium nuclei (alpha particles), transitioning to other elements (see Fig. 2).

Radioactive isotopes of one particular chemical element in these decay chains are quite distinct from the others. The isotopes radon-220 (^{220}Rn) and radon-222 (^{222}Rn) are isotopes of the noble chemical element radon (Rn, Z=84) an odorless, colourless, tasteless radioactive gas, with its properties allowing for significantly different transport properties from seabed to water among others, when compared to the other elements in the natural decay chains. These are the same properties that allow for efficient extraction from water, again compared to the other elements.

A unique radon spectrometer, called αSPECT, is being developed by RAMONES to conduct high-resolution alpha spectrometry underwater, to quantify *in-situ* activities of radon isotopes, along with their variations, which are currently investigated as possible earthquake precursors.

Ocean monitoring for society

The novelty of RAMONES is not limited to developing SoA detectors. Beyond sensor technology and advancements in robotics and marine engineering, RAMONES' *in-situ*, continuous monitoring will provide a wealth of information from remote locations never been visited before. Such radioactivity datasets will be disseminated to various stakeholders (researchers, agencies, citizens and policy makers) to maximize the impact of the innovative technology of RAMONES on human well-being, safety and financial prosperity, through an innovative Risk Information System (RIS).

As the international voices of concern about the impact of climate crisis become stronger day by day, coastal communities, but society in general, can only benefit from such RIS, as the real-time of natural and anthropogenic hazards can increase the resilience of communities and economies against them.

Final remarks

Despite not an extensive and detailed review, this first part of the White Paper has offered some of the essential terms about marine radioactivity and laid the foundation for part II, which will follow. In part II, specific applications of the RAMONES technology will be discussed. The novel solutions, but also the limitations and lessons learned from the field testing of RAMONES sensors will be presented to some detail.

We hope that the White Paper can play the role of a solid first step in inspiring and motivating further research in the marine radioactivity domain, by combining traditional problems with innovative technological approaches.

Acknowledgements

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