DOI: 10.1478/AAPP.99S1A39

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 99, No. S1, A39 (2021)

NATURAL RADIOACTIVITY AND RADIOLOGICAL HAZARD FOR HUMANS: A SIMPLE INTRODUCTION FOR NEWBIES AND STUDENTS. NEW PERSPECTIVES AND INNOVATIVE TEACHING METHODS

DAVIDE ROMANO [a b *], GIUSEPPE SABATINO [a], MARCELLA DI BELLA [b c], FRANCESCO ITALIANO [b], MARIA TERESA CACCAMO [a], ALESSANDRO TRIPODO [a] AND SALVATORE MAGAZÙ [a]

ABSTRACT. Pollution due to natural radioactivity is still a poorly known topic among young people. This paper describes the contents for an introductive university course or lecture conceived in a multitask program. Along with a so-called "flipped" configuration, where students are able to receive didactic materials prior to face-to-face lessons, multimedia contents should be shown to the students, who are at first faced with known anthropogenic accidents. Moreover, field and laboratory experimental activities can provide further insight regarding the radiological assessment strategies. Here, the most important principles and effects concerning the radioactive decay of naturally occurring radionuclides are described. The greatest part of natural radioactivity derives from terrestrial radionuclides occurring in soil and rocks. The radionuclides are atoms characterized by an excess of nuclear energy, which makes them unstable giving rise to decay. The radionuclides emit gamma rays, as well as alpha and/or beta particles. People are constantly subjected to indoor and outdoor exposure due to natural radioactivity. The possible sources can be considered as external due to natural sources located outside the human body, and internal provoked by ingestion or inhalation of radionuclides. The indoor exposure from natural sources is mainly related to radiation from building materials and to radon entering buildings from soils and rocks though cracks in walls and floor. The outdoor exposure mainly accounts for the terrestrial gamma radiation that crosses the soil-air interface, and for the radon emitted from soils in seismic and volcanic areas. In this regard, there is a strong relationship between health diseases (e.g. cancer, necrosis and DNA and RNA modifications) and high-levels of natural radioactivity. For this reason, the radiological assessment of the most vulnerable areas represents a key point in order to mitigate hazard and risk connected to the human exposure to natural radioactivity.

1. Introduction

Radioactivity was discovered by Henry Becquerel in 1896, who detected the radioactive particles emitted from uranium salts during a series of experiments regarding the study of phosphorescence. Becquerel observed that uranium-bearing materials that had not been

exposed to light, were able to cause a blackening of a photographic plate (Becquerel 1883, 1885; Blaufox 1996). Then, by excluding phosphorescence, an undiscovered type of radiation had to be responsible for that type of phenomenon (Becquerel 1896a; Lodge 1912; Badash 1965).

Later, Ernest Rutherford discovered that the elements decay follows an exponential trend, and it is mainly characterized by the transformation of an element into another one (Becquerel 1896b, 1900). Finally, Pierre Curie and Marie Sklodowska (Marie Curie) identified other radioactive elements, such as thorium, polonium and radium. Tonness of pitchblende, a radioactive uranium-rich mineral extracted in Czechoslovakia, were necessary to isolate radium in pure form (Skłodowska-Curie 1898; Gasinska 2016). The Curies were not aware of the dangerous effect of radiation on the human body; on the contrary, they highlighted the curative effect of radium against tumors. Pierre and Maria Curie, who coined the term "radioactivity", received the 1903 Nobel Prize in Physics along with Henry Becquerel. Marie Curie was the first woman to win the Nobel Prize, and she is currently the only woman to win it twice, as she won the 1911 Nobel Prize in Chemistry (Curie and Bemont 1898; Curie and Skłodowska-Curie 1898; Pigeard-Micault 2017).

Radioactivity has fascinated and concerned many people since the Chernobyl accident in 1986. The disaster occurred at one of the four reactors in the Chernobyl nuclear power plant (Ukraine), and was caused by a series of human mistakes as well as some imperfection in the reactor design. A steam explosion dismantled the core and the roof of the no. 4 reactor, releasing in the atmosphere a huge amount of radioactive substances that was transported by winds across all European countries (Kesminiene *et al.* 1997; Tekkel *et al.* 1997; Waddington *et al.* 2017). The impact due to the Chernobyl accident on human activities, health and habits was huge. For the first time the term "radioactivity" was escaping from dictionary, entering in minds and languages of worldwide population (Rahu *et al.* 2006; Jargin 2010; Balonov 2012). In 2001, a severe nuclear accident occurred at the Fukushima-Daiichi nuclear power plant (Japan). It was provoked by a tsunami that swept over the japanese energy production site damaging the reactors cooling systems. In consequence of the accident, a great amount of radioactive substances was released in the atmosphere and ocean (Geng *et al.* 2017; Fesenko *et al.* 2020; Onda *et al.* 2020).

We have to outline that radioactivity is a natural process of the Earth planet since its formation, occurred around 4.6 Ga. Radioactive elements were included in primordial gas and dust which generated the sun and the planets of the solar system. Currently, approximatively the half of the Earth's internal heat budget derives from the radioactive decay of radioisotopes within the Earth. Radioisotopes occur also in human body, but at low concentrations. Moreover, there are two types of radioactivity: natural and artificial radioactivity. Natural radioactivity develops from sources as for instance rocks and soils, whereas the artificial radioactivity is determined by human activities, which involve radioactive materials, e.g. in nuclear energy production and medicine (Michalik *et al.* 2013; Ershov 2020).

In this article, we provide a simple and brief introduction about the natural radioactivity in the perspective of clarifying the effects on the human health. The paper is addressed to young students, and aims to inform them on the basic principles governing the radioactive decay and on the potential radiological hazard for humans.

2. Isotopes and radioactive decay

2.1. Fundamentals about isotopes. Atoms are formed by one or more electrons, and by a nucleus composed of a number of positive electric charge particles called protons, and zero or more particles with no electric charge known as neutrons. Neutron was discovered in 1932 by James Chadwick and in 1994 Nobel prize in Physics was assigned jpintly to Clifford Shull and Bertram Brockhouse with the following motivation: Neutrons tell us where the atoms are, through diffraction experiments as shown by Shull, and what the atoms do, by means of spectroscopy experiments as shown by Brockhouse with a triple axis spectrometer (Rogers 2013; Nesvizhevsky and Villain 2017; Stone *et al.* 2019). Neutron scattering was initially employed, in the sixties, for the investigation of systems of exclusive physical interest (Magazù *et al.* 2012, 2013; Caccamo *et al.* 2017) , but already in the seventies we found lots of application in the Chemistry domain such as in phase transitions and hydrogen bonded systems(Cywinski 1997; Migliardo *et al.* 2013b); the application fields were further widened in the eighties encompassing Engineering, Geology and Biology, expanding its horizon to multidisciplinary condensed matter science (Magazù *et al.* 2011; Migliardo *et al.* 2013a; Joseph 2020).

Electrons, characterized by a negative electric charge, are bound to the nucleus by the electromagnetic force (Vretenar 2005; Stauffer *et al.* 2008). The number of protons in an atom is known as "atomic number" (Z), whereas the total number of protons and neutrons is known as "mass number" (A). A nuclide is a specie of atom characterized by well-defined nuclear properties, such as a specific energy state and a certain number of nucleons (protons and neutrons).

Atoms with equal Z represent the same chemical element; for instance, all atoms having Z=2 are atoms of helium. Isotopes are atoms of the same chemical elements that differ only for the number of neutrons (N), and then they have equal Z and different A. For example, hydrogen (Z=1) has three isotopes: protium (Z=1, A=1), deuterium (Z=1, A=2) and tritium (Z=1, A=3).

Isotopes, and then nuclides, can be stable or unstable. Unstable isotopes are usually called radionuclides or radioisotopes. Protons and neutrons within the nucleus are bound together by nuclear forces. Neutrons have a key role to stabilize the nucleus, since protons, having a positive charge, tend to separate due to the Coulomb force (Kónya and Nagy 2018).

The number of neutrons with respect to the number of protons is fundamental to keep stability. Figure 1 highlights three different scenarios: i) isotopes with Z ranging from 1 to 20 are stable with Z=N; ii) isotopes characterized by with Z values between 20 and 82 are stable with Z<N; iii) all isotopes with Z>82 are unstable.

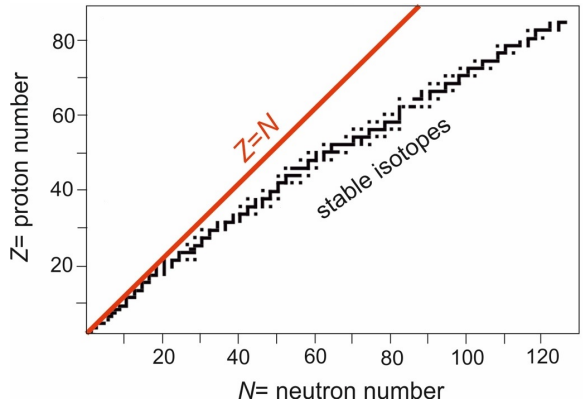

FIGURE 1. Isotope stability with respect to the number of protons (Z) and neutrons (N). Stable isotopes having Z= 1-20, are characterized by an equal number of protons and neutrons (Z=N); stable isotopes with more than 20 protons have more neutrons than protons (Z<N); elements with Z>82 are all unstable (Allègre 2008).

2.2. Radioactive decay. Unstable atoms emit particles and energy with the aim of reach a stable nuclear configuration. This process is known as "radioactive decay" (Choppin *et al.* 2013; Khalaf *et al.* 2019). By emitting particles and energy, a radionuclide (called "parent") transform into a new nuclide (called "daughter"). There are three main modes of decay: alpha, beta and gamma decay (Fig. 2). Other decay mechanisms are known in nature, but they are not treated in this paper.

In the alpha and beta decays, a parent radionuclide transforms into a daughter nuclide with a different number of protons and thereby into a different chemical element. In the alpha decay ($\alpha decay$), the parent radionuclide emits an α particle (helium nucleus) with two protons and two neutrons; therefore, the Z and A values of the daughter nuclide are reduced by 2 and 4 respectively (Fig. 2A). In beta decay, radioisotopes emit beta particles. There are two different types of beta decay: beta- (β^-) and beta+ (β^+), depending on the nature of the beta particle (Silverman *et al.* 1999; Yamada *et al.* 2020). A β^- particle is a fast energetic electron, emitted from a nucleus when a neutron transforms into a proton (Fig. 2B). On the other hand, a β^+ particle is a positron emitted as a result of the conversion of a proton into a neutron (Fig. 2C). For this reason, the β^+ decay is also known as positon emission. As a consequence of a beta decay, the Z value of the daughter nuclides increases by 1 in β^- decay, and decreases by 1 in β^+ decay.

Gamma decay is a conversion of a radionuclide from an excited state to a lower energy state through the emission of gamma ray photons (Fig. 2D).

2.3. Radioactive decay law. The law of radioactive decay is used to express the statistical behaviour of a large number of nuclides. The decrease of a certain number of atoms due to the radioactive decay occurs at a rate, which is proportional to the number of atoms

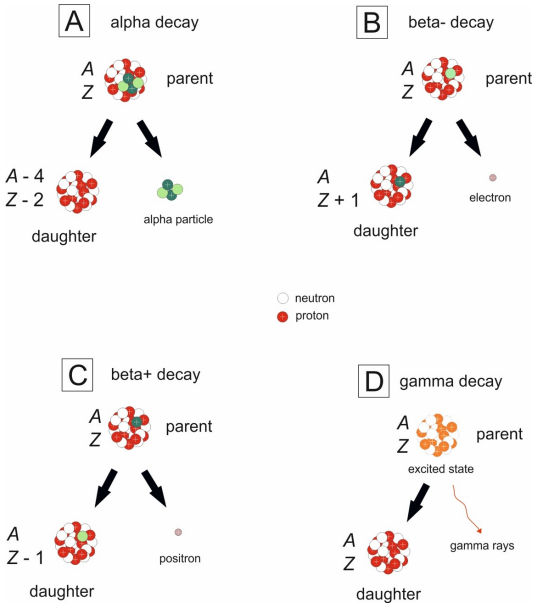

FIGURE 2. A radionuclide (called "parent") transform into a new nuclide (called "daughter") by emitting particles and energy. In this figure, the main types of radioactive decay are illustrated: A) alpha decay: a radionuclide loses an alpha particle composed of two neutrons (light green) and two protons (dark green) transforming into a daughter nuclide reduced by four nucleons; B) beta- decay (β^-): a neutron (light green) transforms into a proton (dark green) and, during the transmutation, a high-energy electron is emitted; C) beta+ decay (β^+): a proton (dark green) transform into a neutron (light green) with the emission of a positron; D) gamma decay: an excited state radionuclide reaches a lower energy state by emitting gamma rays.

(Valković 2019). This process is exponential in time and can be described by the following differential equation:

$$dN/dt = -\lambda N \tag{1}$$

where N is the quantity, t is time and λ is the exponential decay constant. The equation (1) indicates that the probability per unit of time, that a certain nucleus will decay, is constant. This concept can be described through a simple experiment called the "radioactive dice", where a number of dice, symbolizing the radionuclides, are thrown simultaneously. All dice showing the same number, for instance the number 4, are supposed to have "decayed", and then are removed. The remaining "undecayed" dice are counted, and after that, they are thrown again. Those that show the number 4 are removed, whereas the undecayed dice are counted and thrown again. After a number of throws, we can observe that the curve of the undecayed dice displays an exponential trend (Fig. 3).

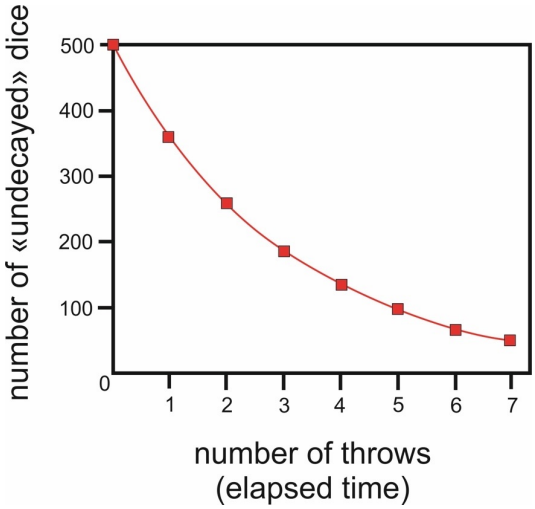

FIGURE 3. The "radioactive dice" experiment, in which a number of dice are thrown simultaneously. All dice showing the same number are deemed to have decayed as radioactive nuclei, and then, they are removed and put aside. The remaining "undecayed" dice are counted and thrown again. This process is repeated for a number of throws, resulting in a reduction in the number of "undecayed" dice as the number of throws increases. The curve of the undecayed dice, against the number of throws, shows and exponential trend and is represented by the differential equation $dN/dt = -\lambda N$

The solution of the equation (1) is:

$$N(t) = N_0 e^{-\lambda t} \tag{2}$$

where N(t) is the quantity at time t and N_0 is the initial quantity (at time t = 0). We have to point out that the decay constant, and then the decay rate, varies among different radionuclides.

The decay rate of a radionuclide can be expressed by two parameters: the mean lifetime and the half-life. The mean lifetime (τ) is the average lenght of time that an atom can live until decay and is calculated as follows:

$$\tau = 1/\lambda \tag{3}$$

The half-life ($t_{1/2}$) respresents the time required for a certain number of radionuclides to reach one half of the initial quantity. The equation that link the decay constant to the half-life is :

$$t_{1/2} = ln2/\lambda \tag{4}$$

2.4. Activity and specific activity. How to calculate the radioactivity? The radioactivity is measured in terms of activity (A), namely the number of disintegration per unit of time. Currently, the unit of measure for A used in the International System is the Bequerel (Bq),

which corresponds at 1 disintegration per second. To describe the amount of radioactivity of a certain material, we have to refer to the total amount of matter. Consequently, the specific activity (also called activity concentration) indicates the activity of a certain radionuclide, with respect to the total quantity of material. For solids, the specific activity is usually expresses in Bq/kg, whereas for gases and liquids is given in Bq/L or Bq/m^3.
The analytical techniques often used to determine the specific activity of radionuclides occurring in solid, liquid and gaseous samples are alpha and gamma spectroscopy, which counts on the fact that alpha particles and gamma rays emitted by a certain isotope have a well defined energy (Kathren and Petersen 1990).

3. Natural radioactivity

The main sources of natural radioactivity are radionuclides produced by cosmic-rays, and primordial radionuclides incorporated into the Earth at the time of its formation.
Cosmic rays come from the sun and from outside of the solar system. They are mainly composed of protons, α particles and electrons of different energy. They enter the Earth's atmosphere generating a cascade of secondary cosmic rays, which are able to reach the Earth's surface. The interaction between cosmic rays and Earth's atmosphere and crust, produce several cosmogenic radionuclides (e.g. ^{3}H,^{10}Be,^{14}C,^{18}F,^{22}Na and ^{24}Na).
Primordial radionuclides, also called terrestrial radionuclides, are abundant within the Earth's crust (i.e. the Earth's outer shell). Moreover, the occurrence of a great amount of terrestrial radioisotopes within the Earth's mantle (i.e. the Earth's intermediate shell) was testified by recent researches (e.g. Agostini *et al.* 2020). The most abundant terrestrial radionuclides are: ^{238}U,^{235}U,^{232}Th and their decay products, ^{40}K,^{87}Rb and ^{187}Re. The three main decay series (or decay chains) known in nature, originated from the terrestrial radionuclides ^{238}U,$^{235}U$and^{232}Th, which are characterized by half-lives comparable to the age of the Earth. Within a decay series, radioisotopes decay into unstable nuclides, which in turn decay aiming for reaching a stable state. These processes generate a sequential series of decays. The series end when a stable progeny forms. All three series end with the generation of a lead isotope. The ^{238}U,^{235}U and ^{232}Th decay series are commonly called the uranium (or radium) series, the actinium series, and the thorium series respectively (Fig. 4).

Terrestrial radionuclides are present in all natural media, from rocks and soils, to waters and air, and they can be physically transported by winds and fluvial waters (Szabó *et al.* 2013; Bezuidenhout 2020). For this reason we can affirm that population is constantly exposed to natural radioactivity, coming from both cosmogenic and terrestrial radioisotopes.

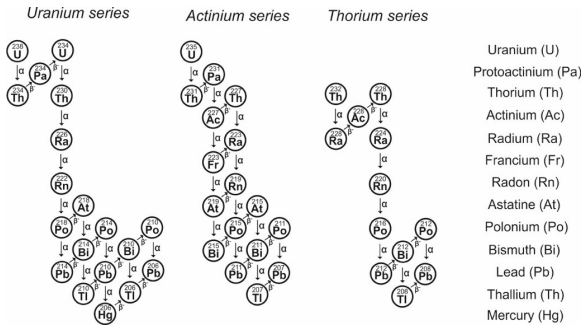

FIGURE 4. Decay chains of ^{238}U (Uranium series), ^{235}U (Actinium series) and ^{232}Th (Thorium series). The decay chains are characterized by a subsequential series of α and $\beta-$ decays. Radionuclides decay, emitting energy and particles, with the aim to reach a stable nuclear configuration. All three series end with the generation of a stable Pb isotope. Full names of elements are in the right side of the figure. The images are modified from the decay chains at https://en.wikipedia.org/wiki/ Decay_chain.

4. Exposure to radioactivity and its effect

4.1. Biological effects and dosimetric quantities. Gamma rays, alpha and beta particles, which are released from decaying radionuclides, behave differently when they interact with matter. Alpha and beta particles can be halted by a sheet of paper and aluminum respectively (Fig. 5); The low and medium penetrating power of alpha and beta radiation respectively, derives to the high to medium ionizing power, thereby the high to medium level of interaction with matter by detaching electrons from atoms (Loevinger *et al.* 1988; Le Grand *et al.* 1991).

Conversely, gamma rays are able to penetrate dense materials, and they can be absorbed by high-density barriers such as lead or concrete shields (Fig. 5). Gamma rays are photons, and then they exhibit physical properties of both waves and particles. Photons have no mass and no charge, and for this reason, they show a less ionizing power than alpha and beta particles.

The health effects induced by natural radioactivity can be important. Living cells can be damaged causing modification and death in some of them. DNA and RNA can be also modified. Radioactivity exposure can give rise to several diseases such as cancer, anemia, necrosis, hereditary effects, and of course also death.

How we assess the potential biological risk for humans induced by radioactivity? For this purpose, a number of radiation quantities are used. The adsorbed dose (D), measured in gray (Gy), is the amount of energy collected in tissue or organs per unit mass (1 Gy= 1 J/kg). Different types of radiation induce different degrees of damages to the human body, then the absorbed dose has to be weighted for the various types and energies of radiation in order to correctly describe the effect for tissues and organs. The equivalent dose (H) was

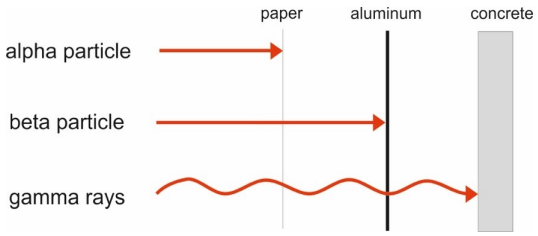

FIGURE 5. Gamma rays, alpha and beta particles behave differently when they interact with matter: alpha and beta particles are stopped by a sheet of paper and aluminum respectively, whereas gamma rays are halted only by high-density barriers (e.g. concrete). This is due to the fact that gamma rays interact with matter less than alpha and beta particles. Then, gamma rays are able to travel over longer distances, while alpha and beta particles have a low penetrating power, resulting in a few centimeters in air.

introduced for this scope; it is measured in sieverts (Sv) and it is calculated by the following formula:

$$H = \Sigma w_R D_{T,R} \tag{5}$$

where $D_{T,R}$ is the mean absorbed dose in tissue or organ T due to radiation R, and w_R is the weighting factor depending on the type and energy of the incident radiation (Kónya and Nagy 2012; Goodhead n.d.). For instance, the weighting factor of alpha particles is 20, while that of gamma rays and beta particles is 1. This is due to the fact that alpha particles have a higher ionising power than beta and gamma radiation, therefore they can cause much more damage on tissues and organs.
The sum of the weighted equivalent doses in all the organs and tissue of the body is called effective dose (E) and it is calculated by the following equation:

$$E = \Sigma w_t H \tag{6}$$

where w_t is the weighting factor for tissue T. The effective dose is measured in sievert as the equivalent dose.

4.2. Exposure. There are two types of exposure: external and internal.

- External irradiation derives from radioactive sources located outside the human body. Gamma rays produced by the radioactive decay of terrestrial radionuclides are the main contribution, especially the gamma radiation emitted from radionuclides in the ^{238}U and ^{232}Th series and from ^{40}K. These radioactive elements, occurring in air, clouds, soils, rocks and in building materials derived from them, induce an average worldwide effective dose of 0.48 mSv per year (UNSCEAR 2000). On the other hand, cosmogenic radionuclides account only for 0.01 mSv per year (UNSCEAR 2000).
- The internal exposure is determined by the intake of radionuclides into the human body. Inhalation and ingestion are the two main processes concurring to the internal exposure. Average worldwide annual effective doses induced by inhalation and

ingestion are 1.26 and 0.29 mSv respectively.
Radon (Rn) is the main contributor to the effective dose induced by inhalation. We will treat an extensive explanation about radioactivity due to radon in paragraph 5.
Dust particles, including uranium and thorium-series radioisotopes suspended in air, produce a minor contribution.
Ingestion of naturally occurring radionuclides depends on their concentration in food and water, and on the consumption rate (i.e. the amount of food and water ingested by a person). The consumption rate for infants and children is around one third and two thirds respectively, with respect to that for adults (UNSCEAR 2000).

5. Hazard for population

According to (UNSCEAR 2000) every people receive a mean of 2.4 mSv per year due to ionizing radiation from natural sources (including also the effect of cosmic rays). This value represents the worldwide average of the annual effective dose, also known as the natural background radiation. In comparison, a chest X-ray analysis induces around 0.1 mSv, whereas a computed tomography of abdomen and pelvis accounts for 6 mSv.
Several factors might cause a considerable increase of the natural background radiation, well above the worldwide average of 2.4 mSv/y, producing significant health hazard. In this paragraph, we analyse the main potential contributors, located indoor and outdoor, able to provoke a dangerous exposure to natural radioactivity.

5.1. Indoor hazards.

5.1.1. *Gamma rays from building materials.* Soils and rocks, which naturally contain radioactive elements, are often used in the construction field. Soils and granular rocks are used as inert material in concrete, and rocks are used as ornamental and pavement stones (Fig. 6).

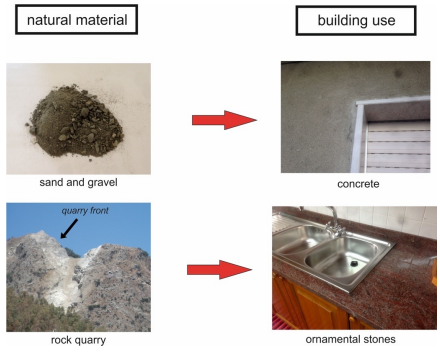

FIGURE 6. Natural materials are extensively used in construction. For instances, sands and gravel are used to produce concrete, whereas rocks are mined and used as ornamental and pavement stones. If rocks and sediments contain a large amount of radionuclides and they are used to create building components, then, their occurrence in walls, floor and furniture could be dangerous.

Building materials can induce high effective doses to humans due to gamma rays emitted from radionuclides inherited from those natural raw materials.
The gamma index I_γ (or "activity concentration index") was proposed to estimate the exposure to gamma rays originated from building materials and it is calculated as following (EC 1999):

$$I_\gamma = C_{Ra}/300\ Bq/kg + C_{Th}/\ 200Bq/kg + C_K/\ 3000Bq/kg \quad (7)$$

where C_{Ra}, C_{Th} and C_K, are the specific activity in Bq/kg of ^{226}Ra,^{232}Th and ^{40}K respectively. Usually, C_{Ra}, C_{Th} and C_K in natural and artificial materials are determined by using gamma spectroscopy.
The gamma index acts as a screening tool to identify building materials potentially inducing an increase, with respect to the natural background dose, higher than 1 mSv.
The dose excess of 1 mSv represents the hazard threshold from the radiation protection point of view.
If the building material is used in bulk amounts (e.g. in concrete), I_γ values >1 produce a dose excess higher than 1 mSv/y, whereas the I_γ value of 0.5 corresponds to a prudential dose excess of 0.3 mSv/y. If natural materials are used as tiles, boards, and other superficial uses, dose excesses of 1 and 0.3 mSv/y are reached with I_γ values of 6 and 2 respectively.
Building materials should be avoided if the increase to the annual effective dose is higher than 1 mSv.

5.1.2. *Radon.* Radon is a radioactive noble gas (Z=86), and is often considered as the greatest contributor to indoor radioactivity. According to several studies (see WHO 2009, and references therein), radon in air is the second cause of lung cancer in population after smoking. Then, determining the indoor activity concentration of radon becomes a key point, since people spend a lot of time in houses and indoor workplaces.
There are two main radon isotopes: ^{222}Rn and ^{220}Rn (also known as thoron). ^{222}Rn belongs to the ^{238}U decay chain, and derives from the ^{226}Ra alpha decay, whereas ^{220}Rn occurs as a product of the alpha decay of ^{224}Ra in the ^{232}Th decay serie (Fig. 4). ^{222}Rn and ^{220}Rn are characterized by a half-life of 3.8 days and 55 seconds respectively. Radon is released from solid materials (i.e. soils, rocks and building materials) and in certain conditions it can be transported far away from the source by carrier gases and groundwater, as explained in paragraph 5.2.2. The radon progeny is composed by radioactive metals such as bismuth, polonium and lead, which decay produces highly dangerous alpha, beta and gamma radiation.
Two processes actually rule the radon emanation from solid materials: alpha recoil and diffusion. The "recoil" is represented by the distance travelled by the "new formed" radon succeeding the alpha decay of the parent radionuclide, whereas the diffusion is the movement of radon atoms from a high density region (solid media) to a region of lower concentration (air or water). Recent studies (see Sakoda *et al.* 2011, and references therein) highlighted the main role of alpha recoil over diffusion.
Only a part of radon generated by radium decay, escapes from the solid media (Fig. 7). The ratio between the number of radon atoms released and generated by the radioactive decay

of radium, is called radon emanation coefficient (or radon emanation factor). This ratio is controlled by various factors such as temperature, moisture, specific surface, size, shape and mineralogy of solid materials (Bikit *et al.* 2011; Sakoda *et al.* 2011; Zhang *et al.* 2019). For instance, the radon emanation coefficient for soils and rocks ranges from around 0.1% to around 40 % (Sakoda *et al.* 2011).

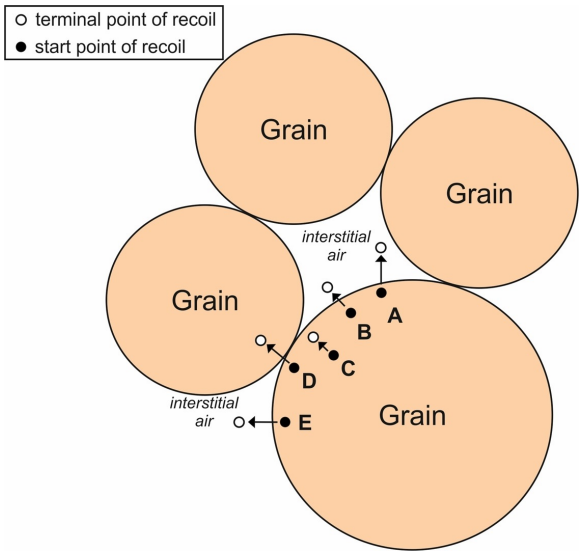

FIGURE 7. The main mechanism of radon emanation from solids is the alpha recoil. The "recoil" is the distance travelled by the "new formed" radon because of the alpha decay of radium. The black dot represents the start location of radium, whereas the white dot is the terminal location of the recoiled "new formed" radon. Only a part of radon escapes from the solid media: in this scheme we can observe that only radon produced by radium atoms A, B and E is emanated from solid grains, while radon generated by radium atoms C and E does no reach the interstitial air, then cannot be emanated (modified from Sakoda *et al.* (2011)).

How does radon enter buildings? There are 3 main potential entrances for radon, as shown in Figure 8: i) radon is continuously released in the soil and rocks interstitial air from minerals, and it can enter buildings from floor and walls cracks and discontinuities. Radon coming from soil and rocks represents the major source to indoor radon. Underground spaces and rooms located at ground floor are the most exposed places; ii) the second major source to indoor radon is supplied by radon emanated from building materials. In buildings located in a temperate climate, this contribution can reach 20% (UNSCEAR 1993); iii) moreover, the contribution of radon dissolved in waters cannot be neglected. In fact, every time water is used, a certain quantity of radon is released in the air. Often, humans are close to water when it is used, and therefore are highly exposed to breathe radon-rich air.

According to WHO (2009), to minimize health hazards, the maximum acceptable level of indoor radon is the annual average of 100 Bq/m^3. The specific activity of radon can be

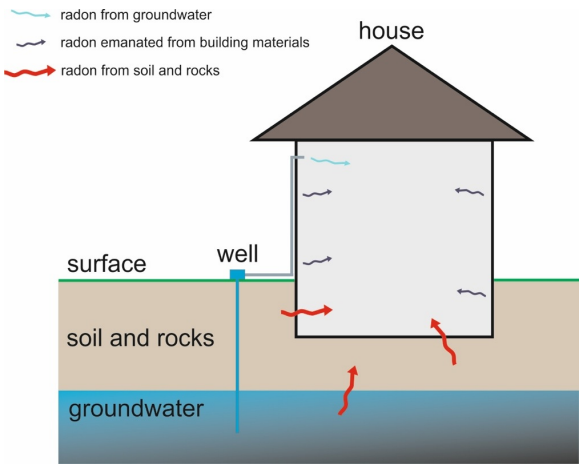

FIGURE 8. Different types of indoor radon pollution: radon is emanated from building materials (dark blue arrows); radon enters buildings from groundwater (light blue arrow) and from soil and rocks (red arrows) due to cracks in walls and floor.

measured by active techniques, often by using commercial available instruments (e.g. alpha spectrometers), and by passive techniques relying on activated materials which absorbs radon atoms (e.g. charcoal).
Prevention and mitigation for indoor radon pollution is a challenge. Two different methods are the following:

(1) Decreasing the number of radon atoms entering houses;
(2) Making building ventilated.

In order to stop most of radon atoms coming from soil and rocks interstitial air, impermeable barriers can be built between soil and floor. In addition, specialized suction systems can be adopted with the aim of removing soil radon before entering buildings. Ventilation is the most effective method against radon emitted from building materials and radon in dissolved waters. In temperate and warm climate zones, the high ventilation rates in building usually prevent the accumulation of high amount of radon. In cold areas, ventilation systems are required to remove stale air and replace it with radon-free fresh air.

5.2. Outdoor hazards.

5.2.1. *Gamma rays from soils and rocks.* The main contribution to the outdoor effective doses is the gamma rays emitted from terrestrial radionuclides in rocks and soils, such as ^{40}K and those in the ^{238}U and ^{232}Th series. Gamma radiation crosses the soil-air interface and produce exposure to humans.
Concerning the radiological hazard assessment connected to the outdoor exposure to terrestrial gamma rays, the specific activity of ^{226}Ra, ^{232}Th and ^{40}K, (indicated by C_{Ra}, C_{Th} and C_K respectively, and expressed in Bq/kg) in rocks and soils is measured and adopted to calculate the absorbed dose and the effective dose.

The absorbed dose in air (D), expressed in nGy/h, is determined by using conversion coefficients (UNSCEAR 2000) through the following equation:

$$D = 0.462\, C_{Ra} + 0.604\, C_{Th} + 0.0417\, C_K \tag{8}$$

Finally, D is used to calculate the annual effective dose (H) expressed in mSv/y:

$$H = D \times 8760(h) \times F/100 \times C \times 10^{-6} \tag{9}$$

where F is the outdoor occupancy factor, and C is the conversion coefficient from absorbed to effective doses. UNSCEAR (2000) suggested adopting the values of 20% and 0.7 Sv/Gy for F and C respectively. The average worldwide effective dose associated to outdoor exposure to terrestrial radionuclides is 0.07 mSv/y (UNSCEAR 2000).
The content of radionuclides in rocks and soils depends on the geological history of these natural materials, including their formation, metamorphism, secondary processes (e.g. weathering and alteration in general), erosion, transport and deposition. Generally, high and potentially dangerous radiation levels are associated with igneous rocks, while low levels with sedimentary rocks.

5.2.2. *Radon emitted from soils in seismic and volcanic settings.* Seismic events are generated by movements along peculiar geological structures known as faults. We can image a fault as a permeable fracture in the Earth's crust that allows to be crossed by water and gases. Earthquakes, micro-seismicity (i.e. magnitude less than zero) and creeping processes (i.e. aseismic movements) in seismic zones, lead to the mechano-chemical generation (i.e. due to rock ruptures) of gases upraising along fractures and fault planes reaching the Earth's surface (Italiano *et al.* 2008). Moreover, active faults are preferential pathways for gases originating in the mantle or produced in the crust by thermal energy (Kissin and Pakhomov 1969; Gianelli 1985).
Gas migration mainly occurs by diffusion due to concentration gradients, or by advection under the influence of external forces such as carrier gases and groundwater flows (Etiope and Martinelli 2002, and references therein). Radon released by rocks can travel by diffusion only a few meters until its activity concentration decreases to less than 1%, with respect to the initial value. Differently, ascending "carrier" gases (e.g. CO_2, CH_4, N_2), are able to create large gas domains that can "carry" rare gases (e.g. radon and helium) over long-distances (Fig. 9).

Another media that is capable of long-distances transport of radon by advection is groundwater. Radon can move into a water media by water displacement or by bubble flows, or it can be dissolved into water moving passively at the same velocity as water (Etiope and Martinelli 2002).

In volcanic zones, carrier gases (mainly CO_2) which transport radon, derives from degassing magma bodies located beneath the Earth's surface. In this environment, carrier gases and secondary components move along faults and fractures affecting volcanic edifices, generating subaerial fumaroles and diffuse degassing areas.

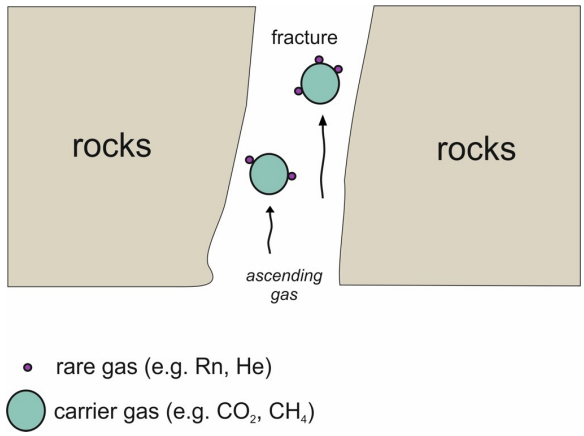

FIGURE 9. Simplified and intuitive model representing the role of carrier gases in redistributing radon. Rock fractures within the Earth's crust allow ascending carrier gases to move towards the Earth's surface transporting radon and other rare gases over long distances. Radon is linked to carrier gases by van der Waals forces.

According to Etiope and Martinelli (Etiope and Martinelli 2002), we can assume that carrier gases and groundwater control the transport and redistribution of radon toward the Earth's surface.

In Figure 10, we can observe how the surface emission of carrier gases together with passively transported-radon, is connected to the occurrence at the Earth's surface of fault planes and fracture zones.

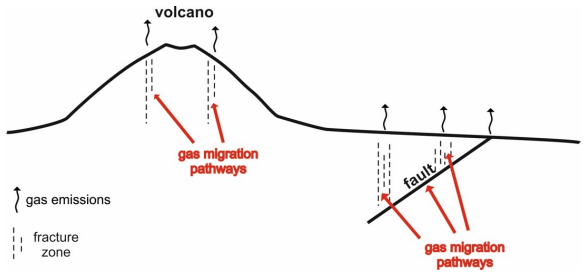

FIGURE 10. Carrier gases (e.g. CO_2 and CH_4) and radon, generated in the Earth's crust or mantle, are able to reach the Earth's surface and atmosphere by migrating along permeable faults and fracture zones. At the Earth's surface the release of gas generates diffuse emission zones that in certain condition can be very dangerous for humans.

Finally, we can state that the radiological hazard due to outdoor radon is greater for people currently living around seismic and volcanic zones.

6. Teaching Method

Regarding the natural radioactivity, we believe that a multi-task learning approach could be the best way to transfer and share knowledge from teachers to students and/or people in general (Neo and Neo 2001; Alvarez and Booth 2013; Caccamo *et al.* 2018). Watching, reading, hearing and doing must be the "four pillars" of this innovative and efficient teaching method (Hirsh-Pasek *et al.* 2015; Caccamo and Magazù 2017, 2018). We can divide the teaching program in three different parts, which should be developed in a precise order, from part one to part three:

(1) learning by watching: Usually, students are very curious about causes and consequences related to the most important anthropogenic accidents, as the Chernobyl and Fukushima ones. A series of television programmes and documentary movies, focused on those dreadful accidents, could be shown in order to inspire students to understand the physicochemical mechanisms governing radioactivity in general (both natural and artificial) (Griffin and Haythorpe 2011).
Goals of part one: promoting student's curiosity and interest about radioactivity; acquiring historical information.

(2) flipped classroom: in this approach course materials are delivered to students prior to face-to-face lessons. The reversed mode might result very useful; in this view, a lot of time can be spent in-class to better describe concepts and phenomena, and make a great number of examples, which are crucial to obtain a more deep learning (Martínez-Jiménez and Ruiz-Jiménez 2020).
Goals of part two: comprehending and learning properties, rules and concepts of natural radioactivity.

(3) learning by doing/thinking: the last part of the program should be spent to involve students in field and laboratory activities. A number of field measurements, such as determination of radon concentration and gamma radiation levels in soils, could be performed by teacher and students. Those kind of surveys have two great advantages: i) they are carried out by means of portable alpha/gamma spectrometers; ii) the results are achieved immediately (Reese 2011). Moreover, rock, soil or water samples could be collected in order to be analysed in laboratory.
Goals of part three: understanding how to perform radiological analyses on different materials and with different techniques; developing a good work ethic; learning how to manage a set of data.

7. Conclusions

This article represents a short introduction to the natural radioactivity and its fall-out to the human's health. We want to stress on the fact that ^{40}K and the radionuclides belonging to the decay series of ^{238}U and ^{232}Th, in particular radon, are the main responsible for the most part of natural radiation levels, both outdoor and indoor. These radionuclides occur in soils, rocks, water and building materials. Therefore, people are constantly exposed to natural radioactivity.Taking into account this consideration, we can affirm that the best method to assess and mitigate the hazard for population due to the natural radioactivity, includes: i) the measurements of radioactivity in soils and rocks in order to quantify the specific activity of terrestrial radionuclides; iii) the shielding of buildings from radon that

coming from soils and rocks, especially in seismic and volcanic areas; iii) the measurements of radioactivity related to raw materials used in construction.

In conclusion, we hope that the information provided in this paper can help the population, in particular the young generation to become aware of the hazard and the risk connected to the natural radioactivity. Moreover, we are confident that this concise paper will be a successful tool in a multitask teaching program, which in our opinion represents the best way to introduce and guide young students into the critical theme of the natural radioactivity.

Aknowledgements

The authors wish to thank the FSE (Fondo Sociale Europeo) Operational Program (OP) for Sicily 2014-2020 for its financial support.

References

Agostini, M. *et al.* (2020). "Comprehensive geoneutrino analysis with Borexino". *Phys. Rev. D* **101**, 012009 [63 pages] (1). DOI: 10.1103/PhysRevD.101.012009.

Allègre, C. J. (2008). *Isotope geology*. Cambridge University Press.

Alvarez, A. and Booth, A. (2013). "Motivated by Meaning: Testing the Effect of Knowledge-Infused Rewards on Preschoolers' Persistence". *Child development* **85**, 783–791. DOI: 10.1111/cdev.12151.

Badash, L. (1965). "Chance favors the prepared mind: Henri Becquerel and the discovery of radioactivity." *Archives Internationales d'Histoire des Sciences* **70–71**, 55–66.

Balonov, M. (2012). "On protecting the inexperienced reader from Chernobyl myths". *Journal of Radiological Protection* **32**(2), 181–189. DOI: 10.1088/0952-4746/32/2/181.

Becquerel, H. (1883). "Phosphorographie de la region infra- rouge du spectre solaire. Longueuer d'onde des principales raies". *Comptes Rendus de l'Académie des Sciences* **96**, 121–124.

Becquerel, H. (1885). "Relations entre l'absorption de la lumiere et l'emission de la phosphorescence dans les composes d'uranium". *Comptes Rendus de l'Académie des Sciences* **101**, 1252–1256.

Becquerel, H. (1896a). "Sur les radiations émises par phosphorescence". *Comptes Rendus de l'Académie des Sciences* **122**, 420–421.

Becquerel, H. (1896b). "Sur les radiations invisibles emises par les corps phosphorescents". *Comptes Rendus de l'Académie des Sciences* **122**, 501–533.

Becquerel, H. (1900). "Sur la transparance de l'aluminum pour les rayonnement du radium". *Comptes Rendus de l'Académie des Sciences* **130**, 1154.

Bezuidenhout, J. (2020). "The investigation of natural radionuclides as tracers for monitoring sediment processes". *Journal of Applied Geophysics* **181**, 104135. DOI: 10.1016/j.jappgeo.2020.104135.

Bikit, I., Mrda, D., Samardzic, S., and Kozmidis-Luburić, U. (2011). "Granulation effects on the radon emanation rate". *Radiation protection dosimetry* **145**, 184–188. DOI: 10.1093/rpd/ncr055.

Blaufox, D. M. (1996). "Becquerel and the discovery of radioactivity:Early concepts". *Seminars in Nuclear Medicine* **26**(3), 145–154. DOI: 10.1016/S0001-2998(96)80019-5.

Caccamo, M. T., Cannuli, A., Calabrò, E., and Magazù, S. (2017). "Acoustic Levitator Power Device: Study of Ethylene-Glycol Water Mixtures". In: vol. 199. 1. DOI: 10.1088/1757-899X/199/1/012119.

Caccamo, M. T., Cannuli, A., and Magazù, S. (2018). "Wavelet analysis of near-resonant series RLC circuit with time-dependent forcing frequency". *European Journal of Physics* **39**(4), aaae77. DOI: 10.1088/1361-6404/aaae77.

Caccamo, M. T. and Magazù, S. (2017). "Variable mass pendulum behaviour processed by wavelet analysis". *European Journal of Physics* **38**(1), 015804. DOI: 10.1088/0143-0807/38/1/015804.

Caccamo, M. T. and Magazù, S. (2018). "Variable length pendulum analyzed by a comparative Fourier and wavelet approach". *Revista Mexicana de Fisica E* **64**(1), 81–86. DOI: 10.31349/revmexfise.64.81.

Choppin, G., Liljenzin, J.-O., Rydberg, J., and Ekberg, C. (2013). "Chapter 5 - Unstable Nuclei and Radioactive Decay". In: *Radiochemistry and Nuclear Chemistry (Fourth Edition)*. Fourth Edition. Oxford: Academic Press, pp. 85–123. DOI: 10.1016/B978-0-12-405897-2.00005-7.

Curie, P. and Bemont, G. (1898). "Sur une nouvelle substance fortemontradioactive contenue dans la pitchblende". *Comptes Rendus de l'Académie des Sciences* **127**, 1215.

Curie, P. and Skłodowska-Curie, M. (1898). "Sur une subsatnce nouvelleradio-active contenue dans la pechblende." *Comptes Rendus de l'Académie des Sciences* **127**, 175.

Cywinski, R. (1997). "Current applications of neutron scattering in condensed matter physics, materials science and engineering". *Physica B: Condensed Matter* **234-236**. Proceedings of the First European Conference on Neutron Scattering, 1239–1241. DOI: 10.1016/S0921-4526(97)00273-1.

Ershov, B. G. (2020). "Natural radioactivity and formation of oxygen in Earth's atmosphere: Decay of radioactive 40K and radiolysis of ocean water". *Precambrian Research* **346**, 105786. DOI: 10.1016/j.precamres.2020.105786.

Etiope, G. and Martinelli, G. (2002). "Migration of carrier and trace gases in the geosphere: an overview". *Physics of the Earth and Planetary Interiors* **129**(3), 185–204. DOI: 10.1016/S0031-9201(01)00292-8.

European Commission (1999). *Radiation protection 112 - Radiological Protection Principles Concerning the Natural Radioactivity of Building Materials*. Tech. rep. URL: https://ec.europa.eu/energy/sites/ener/files/documents/112.pdf.

Fesenko, S., Shinano, T., Onda, Y., and Dercon, G. (2020). "Dynamics of radionuclide activity concentrations in weed leaves, crops and of air dose rate after the Fukushima Daiichi Nuclear Power Plant accident". *Journal of Environmental Radioactivity* **222**, 106347. DOI: 10.1016/j.jenvrad.2020.106347.

Gasinska, A. (2016). "The contribution of women to radiobiology: Marie Curie and beyond". *Reports of Practical Oncology & Radiotherapy* **21**(3), 250–258. DOI: 10.1016/j.rpor.2015.11.006.

Geng, X., Xie, Z., and Zhang, L. (2017). "Influence of emission rate on atmospheric dispersion modeling of the Fukushima Daiichi Nuclear Power Plant accident". *Atmospheric Pollution Research* **8**(3), 439–445. DOI: 10.1016/j.apr.2016.10.013.

Gianelli, G. (1985). "On the origin of geothermal CO2 by metamorphic processes". *Bollettini della Società Geologica Italiana* **104**, 575–584.

Goodhead, D. (n.d.). "Relationship of microdosimetric techniques to applications in biological systems". In: *The Dosimetry of Ionizing Radiation, Vol.2*. Ed. by K. Kase, B. Bjarngaard, and F. Attix. Orlando, FL: Academic Press, pp. 1–89.

Griffin, A. S. and Haythorpe, K. (2011). "Learning from watching alarmed demonstrators: does the cause of alarm matter?" *Animal Behaviour* **81**(6), 1163–1169. DOI: 10.1016/j.anbehav.2011.02.022.

Hirsh-Pasek, K., Zosh, J., Golinkoff, R., Gray, J., Robb, M., and Kaufman, J. (2015). "Putting Education in "Educational" Apps: Lessons From the Science of Learning". *Psychological Science in the Public Interest* **16**(1), 3–34. DOI: 10.1177/1529100615569721.

Italiano, F., Martinelli, G., and Plescia, P. (2008). "CO_2 Degassing over Seismic Areas: The Role of Mechanochemical Production at the Study Case of Central Apennines". *Pure and Applied Geophysics* **165**, 75–94. DOI: 10.1007/s00024-007-0291-7.

Jargin, S. (2010). "Overestimation of Chernobyl consequences: Poorly substantiated information published". *Radiation and Environmental Biophysics* **49**, 743–745. DOI: 10.1007/s00411-010-0313-1.

Joseph, A. (2020). "Neutron spectroscopy techniques". In: pp. 355–378. DOI: 10.1016/B978-0-12-819459-1.00013-1.

Kathren, R. and Petersen, G. (1990). "Units and terminology of radiation measurement: A primer for the epidemiologist". *American journal of epidemiology* **130**, 1076–87. DOI: 10.1093/oxfordjournals.aje.a115435.

Kesminiene, A., Kurtinaitis, J., and G., R. (1997). "The study of Chernobyl clean-up workers from-Lithuania." *Acta medica Lituanica* **2**(2), 55–61.

Khalaf, H. N. B., Mostafa, M. Y., and Zhukovsky, M. (2019). "A combined system for radioactive aerosol size distribution measurements of radon decay products". *Radiation Physics and Chemistry* **165**, 108402. DOI: 10.1016/j.radphyschem.2019.108402.

Kissin, I. and Pakhomov, S. (1969). "A contribution to the geochemistry of carbon dioxide in deep zones of underground hydrosphere". *Geokhimiya* **4**. (in Russian), 450–471.

Kónya, J. and Nagy, N. M. (2012). *Nuclear and Radiochemistry*. Elsevier, pp. 49–82.

Kónya, J. and Nagy, N. M. (2018). "Chapter 4 - Radioactive Decay". In: *Nuclear and Radiochemistry (Second Edition)*. Ed. by J. Kónya and N. M. Nagy. Second Edition. Elsevier, pp. 49–84. DOI: 10.1016/B978-0-12-813643-0.00004-4.

Le Grand, J., Roux, Y., Meckbach, R., Jacob, P., Hedemann Jensen, P., and Thykier-Nielsen, S. (1991). "External exposure from airborne radionuclides". In: *Proceedings of the seminar on methods and codes for assessing the off-site consequences of nuclear accidents. Preprint. Volume 1*. Vol. EUR-13013(v.1), pp. 385–406.

Lodge, O. (1912). "Becquerel memorial lecture". *Journal of Chemical Society* **101**, 2004–2043.

Loevinger, R., Budinger, T., and Watson, E. (1988). *Primer for Absorbed Dose Calculations*. New York: The Society of Nuclear Medicine.

Magazù, S., Migliardo, F., and Benedetto, A. (2011). "Elastic incoherent neutron scattering operating by varying instrumental energy resolution: Principle, simulations, and experiments of the resolution elastic neutron scattering (RENS)". *Review of Scientific Instruments* **82**(10), 105115. DOI: 10.1063/1.3641870.

Magazù, S., Migliardo, F., Benedetto, A., Calabrò, E., La Torre, R., and Caccamo, M. T. (2013). "Sucrose: Properties, Biosynthesis and Health Implications". In: *Bioprotective effects of sucrose and trehalose on proteins*. Ed. by S. Magazù. Biochemistry Research Trends. Hauppauge, New York: Nova Science Publisher, pp. 35–46.

Magazù, S., Migliardo, F., and Caccamo, M. T. (2012). "Innovative wavelet protocols in analyzing elastic incoherent neutron scattering". *Journal of Physical Chemistry B* **116**(31), 9417–9423. DOI: 10.1021/jp3060087.

Martínez-Jiménez, R. and Ruiz-Jiménez, M. C. (2020). "Improving students' satisfaction and learning performance using flipped classroom". *The International Journal of Management Education* **18**(3), 100422. DOI: 10.1016/j.ijme.2020.100422.

Michalik, B., Brown, J., and Krajewski, P. (2013). "The fate and behaviour of enhanced natural radioactivity with respect to environmental protection". *Environmental Impact Assessment Review* **38**, 163–171. DOI: 10.1016/j.eiar.2012.09.001.

Migliardo, F., Caccamo, M. T., and Magazù, S. (2013a). "Elastic incoherent neutron scatterings wavevector and thermal analysis on glass-forming homologous disaccharides". *Journal of Non-Crystalline Solids* **378**, 144–151. DOI: 10.1016/j.jnoncrysol.2013.06.030.

Migliardo, F., Magazù, S., and Caccamo, M. T. (2013b). "Infrared, Raman and INS studies of polyethylene oxide oligomers". *Journal of Molecular Structure* **1048**, 261–266. DOI: 10.1016/j.molstruc.2013.05.060.

Neo, M. and Neo, K. T. K. (2001). "Innovative Teaching: Using multimedia in a problem-based learning environment". *Educational Technology & Society* **4**.

Nesvizhevsky, V. and Villain, J. (2017). "The discovery of the neutron and its consequences (1930–1940)". *Comptes Rendus Physique* **18**(9). Science in the making: The Comptes rendus de l'Académie des sciences throughout history, 592–600. DOI: 10.1016/j.crhy.2017.11.001.

Onda, Y., Sweeck, L., Shinano, T., Dercon, G., Yi, A., and Kato, H. (2020). "Soil and vegetation sampling during the early stage of Fukushima Daiichi Nuclear Power Plant accident and the implication for the emergency preparedness for agricultural systems". *Journal of Environmental Radioactivity* **223-224**, 106373. DOI: 10.1016/j.jenvrad.2020.106373.

Pigeard-Micault, N. (2017). "arie Curie, la reconnaissance institutionnelle, des Nobels aux Académies". *Bulletin de l'Académie Nationale de Médecine* **201**(7–9), 1269–1279.

Rahu, M., Rahu, K., Auvinen, A., Tekkel, M., Stengrevics, A., Hakulinen, T., Boice, J., and Inskip, P. (2006). "Cancer risk among Chernobyl cleanup workers in Estonia and Latvia, 1986–1998". *International journal of cancer* **119**, 162–168. DOI: 10.1002/ijc.21733.

Reese, H. (2011). "The learning-by-doing principle." *Behavioral Development Bulletin* **17**, 1–19. DOI: 10.1037/h0100597.

Rogers, J. (2013). "The Neutron's Discovery - 80 dates on". *Physics Procedia* **43**. The 7th International Topical Meeting on Neutron Radiography (ITMNR-7), 1–9. DOI: 10.1016/j.phpro.2013.03.001.

Sakoda, A., Ishimori, Y., and Yamaoka, K. (2011). "A comprehensive review of radon emanation measurements for mineral, rock, soil, mill tailing and fly ash". *Applied Radiation and Isotopes* **69**(10), 1422–1435. DOI: 10.1016/j.apradiso.2011.06.009.

Silverman, M., Strange, W., Silverman, C. R., and Lipscombe, T. (1999). "Tests of α-, β-, and electron capture decays for randomness". *Physics Letters A* **262**(4), 265–273. DOI: 10.1016/S0375-9601(99)00668-4.

Skłodowska-Curie, M. (1898). "Rayon semis par les composes del'Uranium et du Thorium". *Comptes Rendus de l'Académie des Sciences* **126**, 1101–1103.

Stauffer, E., Dolan, J. A., and Newman, R. (2008). "Chapter 3 - Review of Basic Organic Chemistry". In: *Fire Debris Analysis*. Ed. by E. Stauffer, J. A. Dolan, and R. Newman. Burlington: Academic Press, pp. 49–83. DOI: 10.1016/B978-012663971-1.50007-5.

Stone, M., Crow, L., Fanelli, V., and Niedziela, J. (2019). "Characterization of shielding materials used in neutron scattering instrumentation". *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **946**, 162708. DOI: 10.1016/j.nima.2019.162708.

Szabó, Z., Völgyesi, P., Nagy, H., Szabó, C., Kis, Z., and Csorba, O. (2013). "Radioactivity of natural and artificial building materials – a comparative study". *Journal of Environmental Radioactivity* **118**, 64–74. DOI: 10.1016/j.jenvrad.2012.11.008.

Tekkel, M., Rahu, M., Veidebaum, T., Hakulinen, T., Auvinen, A., Rytomaa, T., Inskip, P., and Boice, J. (1997). "The Estonian Study of Chernobyl Cleanup Workers: I. Design and Questionnaire Data". *Radiation research* **147**(5), 641–652. DOI: 10.2307/3579631.

United Nations Scientific Committee on the Effects of Atomic Radiations Sources, Effects and Risks of Ionizing Radiation (1993). *Sources and Effects of Ionizing Radiation*. Tech. rep. REPORT Vol. I. URL: https://www.unscear.org/unscear/en/publications/1993.html.

United Nations Scientific Committee on the Effects of Atomic Radiations Sources, Effects and Risks of Ionizing Radiation (2000). *Sources and Effects of Ionizing Radiation*. Tech. rep. REPORT Vol. I. URL: https://www.unscear.org/unscear/en/publications/2000_1.html.

Valković, V. (2019). "Chapter 1 - Radioactive nuclides in nature". In: *Radioactivity in the Environment (Second Edition)*. Ed. by V. Valković. Second Edition. Elsevier, pp. 1–29. DOI: 10.1016/B978-0-444-64146-5.00001-X.

Vretenar, D. (2005). "Nuclear structure far from stability". *Nuclear Physics A* **751**. Proceedings of the 22nd International Nuclear Physics Conference (Part 1), 264–281. DOI: 10.1016/j.nuclphysa.2005.02.010.

Waddington, I., Taylor, R., Jones, R., and Thomas, P. (2017). "J-value assessment of the cost effectiveness of UK sheep meat restrictions after the 1986 Chernobyl accident". *Process Safety and Environmental Protection* **112**, 114–130. DOI: 10.1016/j.psep.2017.08.018.

World Health Organization (2009). *Handbook on indoor Radon: a public health perspective*. Tech. rep. URL: https://apps.who.int/iris/handle/10665/44149.

Yamada, T., Sato, Y., Yunoki, A., and Kawada, Y. (2020). "α-particle discrimination in the measurement of α/β decaying chains by the use of ultra-thin plastic scintillation sheets". *Applied Radiation and Isotopes* **159**, 109069. DOI: 10.1016/j.apradiso.2020.109069.

Zhang, W., Zhang, Y., and Sun, Q. (2019). "Analyses of Influencing Factors for Radon Emanation and Exhalation in Soil". *Water, Air, & Soil Pollution* **230**, 16. DOI: 10.1007/s11270-018-4063-z.

[a] Università degli Studi di Messina
Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra
Viale F. Stagno d'Alcontres 31, 98166 Messina

[b] Istituto Nazionale di Geofisica e Vulcanologia Sezione di Palermo
Via Ugo La Malfa 153, 90146 Palermo, Italy
Via dei Mille 44, 98057 Milazzo, Messina, Italy

[c] Stazione Zoologica Anton Dohrn (SZN)
Villa Comunale, 80121 Napoli, Italy

[*] To whom correspondence should be addressed | email: dromano@unime.it

Paper contributed to the international workshop entitled "New Horizons in Teaching Science", which was held in Messina, Italy (18–19 november 2018), under the patronage of the *Accademia Peloritana dei Pericolanti*
Manuscript received 17 November 2020; published online ZZ Month 2021