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SIMULATION OF RADIOLUMINESCENCE INDUCED BY ALPHA PARTICLES IN THE AIR BY THE MONTE CARLO METHOD

Ioana Lalau[1,2*], Mihail-Razvan Ioan[1]

[1]Horia Hulubei National Institute of Physics and Nuclear Engineering, Magurele, Romania
[2]University of Bucharest, Faculty of Physics, Magurele-Bucharest, Romania

Abstract. *In the last period the alpha-induced luminescence of air was proposed to be utilized for remote detection of alpha emitting from radioactive waste sources or for rapid radon detection. The aim of this study is to investigate the possibility to discriminate between the radioluminescence signal and Cherenkov photons due to the simultaneous presence of alpha and beta sources in the same container. Alpha particles induce radioluminescence when absorbed in air. The photons are emitted in the near ultraviolet region by nitrogen molecules excited by secondary electrons. The accurate knowledge of the radioluminescence yield is of the utmost importance for novel radiation detection applications utilizing this effect. On the other hand, the energetic electrons from the beta spectra can produce Cherenkov radiation in air in the same wavelengths as the photons emitted by deexcitation of nitrogen molecules. When alpha and beta emitting radionuclides are simultaneously present in sample, the detector must be able to discriminate between these contributions. We determine the number of photons produced per unit area (photon flux) by deexcitation of nitrogen molecules and also the number of photons in the same wavelength range produced by beta particles when passing through air.*

Key words: *Alpha particles, FLUKA, radioluminescence, simulations*

1. INTRODUCTION

Alpha emitting radionuclides can cause severe damage if are ingested or inhaled [1]. So, alpha sources detection constitutes a major problem for personnel working in nuclear safety field.

Due to high linear energy transfer and high stopping power, alpha particles have a short range (few centimeters in air) [2] and they are conventionally detected in the proximity of the source. Traditional detectors (with scintillation, gas, semiconductor) used for alpha particles detection, are based on the direct interaction between particles and sensitive volume of the detector. Because conventional detectors are positioned close to the source, the personnel may be exposed to additional risks, which necessitates the use of protective equipment and a significant amount of time.

Therefore, a new method of alpha particles detection it's necessary and for this purpose, radioluminescence process can be used [3]. The radioluminescence light of air consists of ultraviolet (UV) photons which are emitted by nitrogen molecules [4]. Radioluminescence light can be transmitted through air on a significant distance, few orders of magnitude greater than mean free path of alpha particles in air.

During passage through media, alpha particles with energies in the MeV range can ionize a large number of molecules.

The released electrons following the ionization process gather kinetic energy, and the so-called secondary electrons can ionize and excite other molecules, according to the conservation of momentum. The thermalization of alpha particles occurs after hundreds of collisions [5].

Nitrogen molecules excited by secondary electrons generate fluorescence light in the near ultraviolet region (300 ÷ 400) nm. The aforementioned process also applies to beta particles.

The scope of this study is to use the atmosphere as a scintillator, and the emission of molecular and ionized nitrogen are used for this purpose.

2. METHODS

2.1. General principles

Nitrogen has several narrow emission peaks at the near UV region. Other atmospheric gases might be used as a scintillator but they have weak emissions or are located at less desirable wavelengths [6].

Secondary electrons produced in the ionization process by alpha particles, have the greatest contribution to the nitrogen excitation. The 2P band of the nitrogen molecule cannot be directly excited from ground state, since this would require transition from a singlet to a triplet state. The excitation is possible via an exchange of low energy electron [7, 8].

* ioana.lalau@nipne.ro

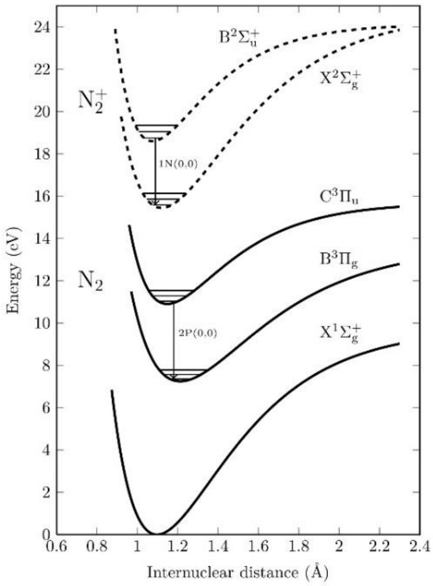

Figure 1. Selected energy levels of N_2 molecule illustrated with Morse potential plots, using molecular constants from Lofthus and Krupenie [9]

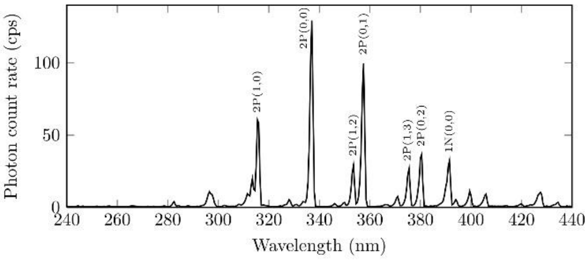

Figure 2. Radioluminescence emission spectrum of air excited by Am-241 alpha particles [10]

$$e_s^-(\uparrow) + N_2(X^1\Sigma_g^+) \rightarrow N_2^*(C^3\Pi_u) + e_t^-(\downarrow) \quad (1)$$

The secondary electron excites the nitrogen molecule in the ground state, so the molecule is in an excited state and the electron is thermalized. This is the main excitation path for neutral nitrogen molecule [11].

Also, it's possible that some of the excitation arises from the recombination of ionized molecule [8]

$$e_s^- + N_2^+(X^2\Sigma_g^+) \rightarrow N_2^*(C^3\Pi_u) \quad (2)$$

The once ionized molecule emits light in the 1N system. The excitation takes place at the same time with the ionization.

$$e_s^- + N_2(X^1\Sigma_g^+) \rightarrow N_2^{+*}(B^2\Sigma_u^+) + e_t^- + e_s^- \quad (3)$$

The effectiveness of secondary electron excitation is strongly reliant on their energy. The maximum effective excitation of the 2P band system is found with 14-15 eV electrons [12-16].

The goal of this work is to model the photon fluence produced by alpha particles in air at a significant distance from the source.

Monte Carlo techniques are now very useful for modelling problems with significant uncertainty, and their applications are quite diverse, including physical sciences, engineering, computational biology, and so on.

They are a subset of computational processes that use the method of repetitive random sampling in order to make numerical approximations of unknown parameters and permit the modelling of complex circumstances where many random variables are involved while evaluating the impact of risk.

2.2. FLUKA Code

FLUKA is a Monte Carlo code, first developed at CERN used for calculation of particle transport with matter, with a wide range of applications including shielding, activation, dosimetry, radiotherapy, and so on. It can simulate with high precision the interaction and propagation in matter of roughly 60 different particles, including photons and electrons with energies from 1 keV up to thousands of TeV, neutrons down to thermal energies and heavy ions. Another advantage of FLUKA is that it can handle even very complex geometries [17, 18].

The code's input comprises of several cards, each belonging to a distinct category. Each card has one keyword (the name of the command), six floating point values called WHATs and one character string called SDUM [17, 18].

FLUKA is able to produce and propagate optical photons of Cherenkov, scintillation and transition radiation light. Light generation is disabled by default and must be activated and completely controlled by the user via data cards and user routines.

In this paper, it has been estimated the photon fluence induced by charged particle in air. In order to perform the simulation, we considered a volume of air of 2.5 x 2.5 x 2.5 m^3 in which the alpha and beta particles have been generated. In the simulation we have considered two processes: the production in air of Cherenkov and Scintillation light (Radioluminescence). Because the code does not perform any physics checks on the light yield and material properties, we defined the optical properties of air: the refraction index as a function of wave-length (or frequency or energy), the reflection coefficient, and so on, as well as the relative intensities of the peaks from the literature.

Optical photons are treated according to the laws of geometrical optics. From the physics point of view, optical photons have a certain energy (sampled according to the generation parameters given) and carry along their polarisation information. Cherenkov photons are produced with their expected polarisation, while scintillation photons are assumed to be unpolarised. At each reflection or refraction, polarisation is modified according to optics laws derived from Maxwell equations. Optical photons can be quenched or elastically scattered (Rayleigh scattering) so we defined also an absorption coefficient and a diffusion coefficient for air.

The air used is the default air implemented in FLUKA.

The FLUKA simulations were performed with 5 x 103 alpha particles histories and 1 x 104 beta particles histories.

We utilized the FLuka Advanced InteRface (FLAIR), which is a useful graphical user interface for running FLUKA, for all the simulations reported later in this work [19].

2.3. EXPACS

EXPACS stands for "EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum". It can instantaneously calculate terrestrial cosmic ray fluxes of neutrons, protons, ions with charge up to 28 (Ni), muons, electrons, positrons, and photons nearly anytime and anywhere in the Earth's atmosphere [20-22].

EXPACS was used in this paper to calculate terrestrial cosmic ray fluxes of electrons and positrons at IFIN-HH (Magurele, Romania). To estimate the fluxes, we specified the input parameters like: geographic coordinates, altitude, W-index that expresses the solar activity, time, surrounding environment and input local effect parameter.

3. Results and discussion

Simulations of alpha incident particles with a 5 MeV energy have been carried out using the FLUKA code. The statistical errors of the results in all simulations were found in the range of 1-3%. The fluence of photons produced by alpha in the air as a function of wavelength was scored at various distances from the source. For the purpose of this study, which is to investigate the feasibility of radioluminescence process for remote detection of alpha particles, we chose the distance of 2.5 meters from the source to reduce the risk of exposure of the personnel to other types of radiation present in the investigated area. At the specified distance we can observe in Figure 3 that a single alpha particle with a 5 MeV energy produces 800 photons/cm^2 with a wavelength of 337 nm.

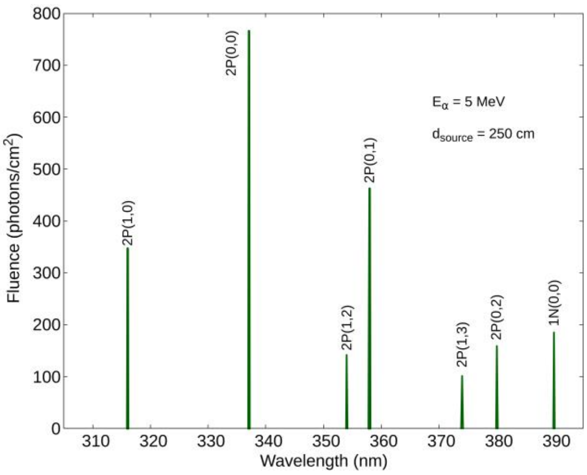

Figure 3. Simulated radioluminescence emission spectrum of air excited by alpha particles

Depending on the background contribution, one has to choose the proper distance for which the contribution of radioluminescence it's significant for the detection of alpha sources.

The decrease of the photon fluence with the distance it's highlighted in Figure 4 by the photon density plot.

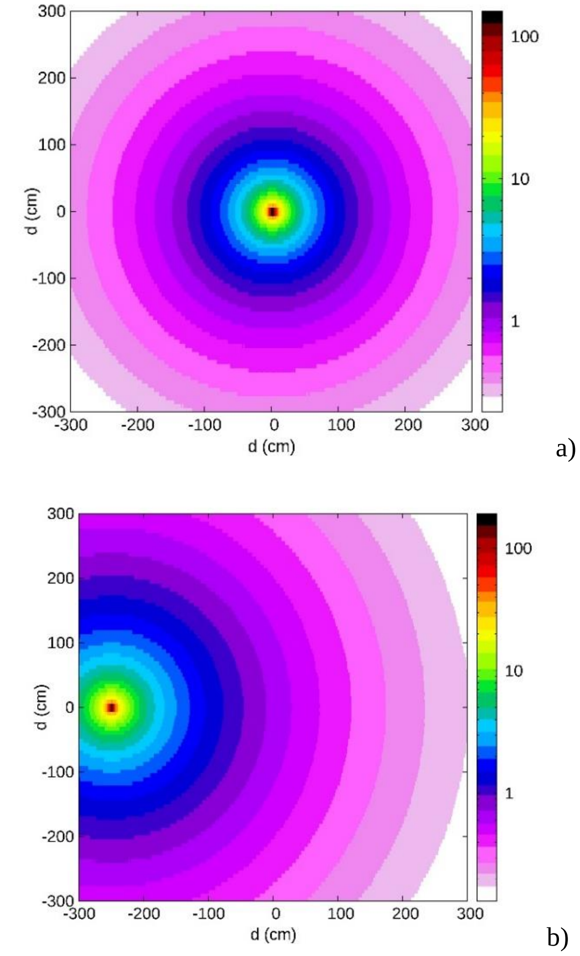

Figure 4. Photon density (photons/cm^3) projections: a) on yz plane and b) on xy plane

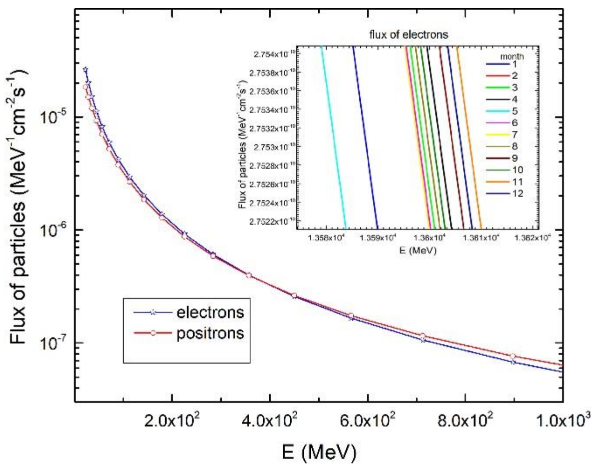

Figure 5. Electron and positron cosmic ray flux estimated by EXPACS

Although theoretically desirable, there are also considerable difficulties with using the radioluminescence approach. The main issue that needs to be overcome is separating alpha-induced air-radioluminescence from background UV radiation. For example, in the wavelength region of (300÷400) nm, the most important contribution to the background, it's from cosmic rays: beta particles.

To estimate the background contribution from cosmic rays EXPACS was used. From the Figure 5 it can be observed that there are very small differences between fluxes calculated every month.

Furthermore, the data (Figure 6) shows that positrons have a greater contribution to the photon fluence than electrons.

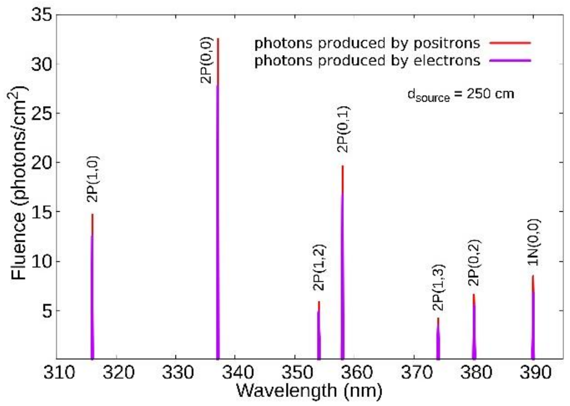

Figure 6. Radioluminescence induced by electrons and positrons from cosmic rays per primary incident particle

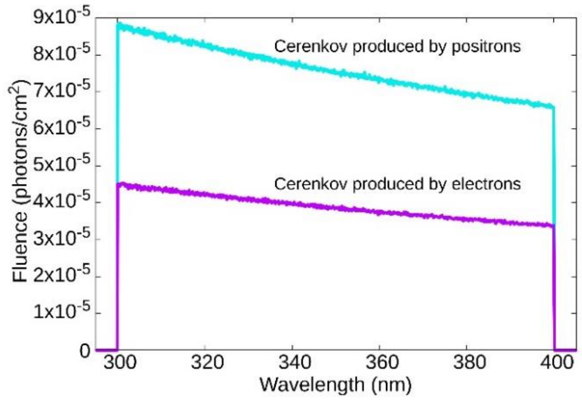

Figure 7. Cerenkov photons produced by beta in air

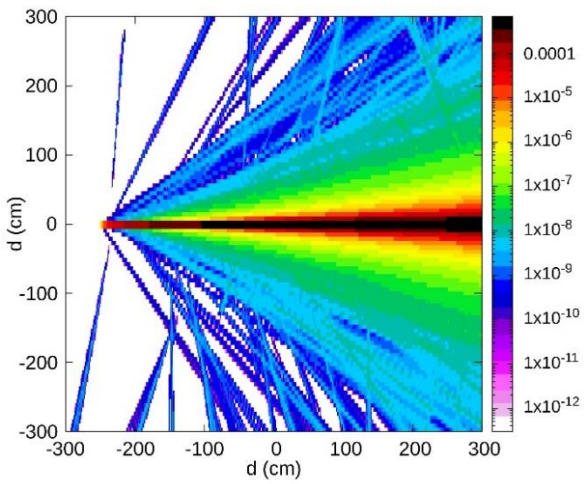

Figure 8. Cerenkov photons density projection on xy plane

Another important process that occurs when beta particles interact with air is Cerenkov Effect. Beta particles from cosmic ray spectrum have energies greater than 22 MeV (the minimum energy of beta particles to produce Cerenkov effect in air) so they can produce Cerenkov radiation with the wavelength range of interest (300÷400) nm as it can be observed in Figure 7 and in Figure 8.

Next are presented all the results obtained in the simulations. It can be observed that the photons emitted following nitrogen excitation by cosmic rays (beta particles here) have a contribution of 4% to the total number of photons produced on the surface. The Cerenkov radiation produced by cosmic rays it's negligible.

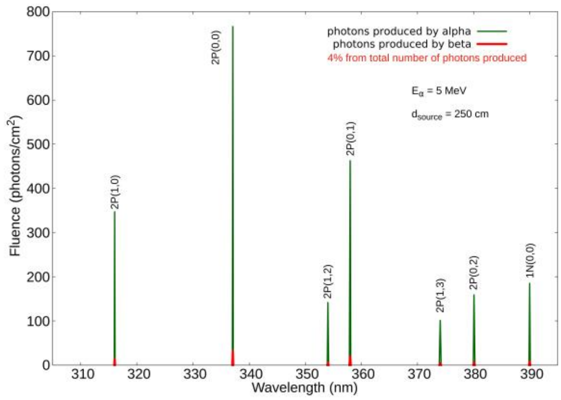

Figure 9. Simulated radioluminescence emission spectrum of air excited by alpha and beta particles

4. Conclusion

Considering the results from the simulation with their uncertainties (between 1-3%) and taking into account the background contributions from cosmic rays (4%), we proved that the radioluminescence process may be used to detect alpha emitting sources but also other charged particles.

From the simulations, we obtained the Cerenkov and beta induced radioluminescence spectra.

Air fluorescence is well suited for the detection and localization of alpha emitters.

Further study needs to be done for other background sources.

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