Fusion Engineering and Design 131 (2018) 125–129

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Monte Carlo simulation of tritium beta-ray induced X-ray spectrum in various gases

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ARTICLE INFO

Keywords:
Tritium beta-ray induced X-ray spectrometry
Bremsstrahlung
Monte Carlo simulation
Geant4

ABSTRACT

Tritium beta-ray induced X-ray spectra in various gas mediums were simulated by Monte Carlo simulation using Geant4 tool kit. The simulated beta-ray induced X-ray spectrum (s-BIX spectrum) was composed of the bremsstrahlung component and characteristics X-rays from constituent elements. The total number of photons in s-BIX spectrum decreased with increasing pressure of medium except argon. In argon medium, the characteristics X-ray of argon was generated by beta particles from tritium decay, and the contribution of Ar-Kα and -Kβ compensated the reduction of bremsstrahlung generated by solid matter with increasing argon pressure. At 0.001 atm of medium pressure, the total counts in s-BIX spectrum was independent from gas medium. Therefore, the gas medium dependence in BIXS at low pressure (less than 0.001 atm) was not serious issue.

1. Introduction

The beta-ray induced X-ray spectrometry (BIXS) is one of the promising methods of tritium analysis. The BIXS has been developed and applied to high-activity tritium gas analysis [1–7]. The Karlsruhe Tritium Neutrino Experiment (KATRIN) requires high stability activity monitor for gaseous tritium, and various tritium measurement systems by the BIXS have been developed [8–10]. The principle of BIXS is as follows [11], the beta particle with tritium decay travels in matter and its kinetic energy is reduced by both the ionization process of atoms and the electromagnetic radiation process (bremsstrahlung). In the ionization process, the characteristics X-ray is generated by the de-excitation of an excited atom. In the electromagnetic radiation process, the beta particle is deflected by the nuclear charge, and the kinetic energy of beta particle is reduced. The reduced energy is transformed to the bremsstrahlung radiation. Since the intensity of the radiation is proportional to the number of beta particles colliding with matter, the activity of tritium can be evaluated from the intensity of radiation induced by the beta particle from tritium decay. The penetration length of electromagnetic radiation is longer than the range of beta particles, and a conventional low energy X-ray detector can detect these radiations from the outside of a gas line.

The BIXS for tritium analysis in gas phase has some superior features in comparison with a gas flow ionization chamber or a proportional counter [1–3,7,10]. However, no gas cell used for the BIXS is commercially available. Users must build and design their own BIXS. To design a gas cell, a Monte Carlo simulation for tritium analysis was programmed for the BIXS using Geant4 toolkit (version 10.01.p02) [12]. The beta-ray induced spectrum calculated by this program coincided with the observed one. This program was also used to obtain an optimum gas cell design [12].

For gas phase tritium analysis by the BIXS, the dependence of gas medium on obtaining accurate values of tritium activity is an important issue. Because the range of beta particle is changed by the density of gas medium, and the yield of bremsstrahlung depends on the nuclear charge of the atom in the gas medium. However, it is difficult to prepare tritium mixture with nitrogen, oxygen and rare gases at a given activity. The dependence of gas medium in the BIXS was studied using the Monte Carlo simulation. Calculation results showed the effect of medium gas pressure and the dependence of the counting efficiency on various gas mediums.

2. Monte Carlo simulation

The Monte Carlo simulation for the BIXS was programmed with using Geant4 toolkit (version 10.01.p02) [13,14]. The simulation program was used for a design of gas cell for the BIXS in the literature presented by the authors [12]. In this program the electromagnetic

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https://doi.org/10.1016/j.fusengdes.2018.04.080
Received 11 September 2017; Received in revised form 22 January 2018; Accepted 19 April 2018
Available online 01 May 2018

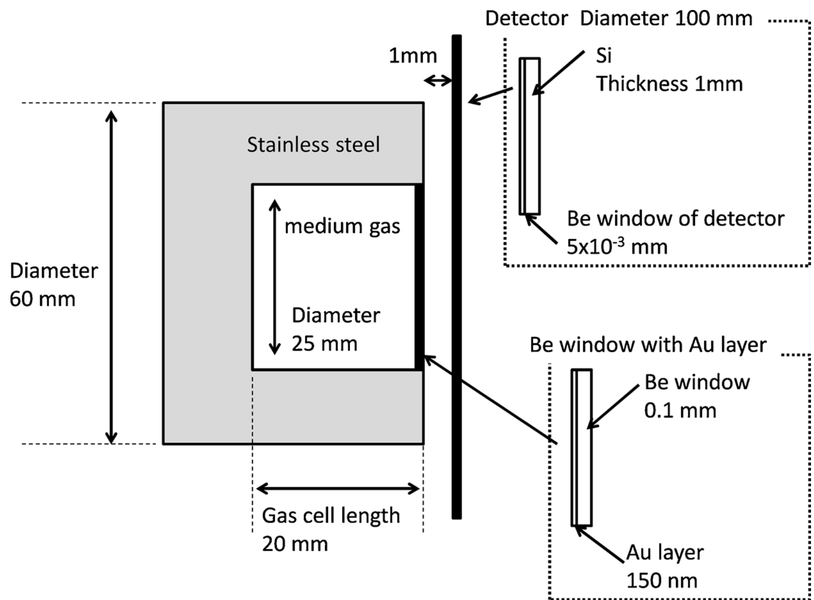

Fig. 1. Geometry of BIXS gas cell on Monte Carlo simulation. The gas cell is a cylinder with a cylindrical inner space for holding medium gases.

interactions between particles and constituent atoms were described by the PENELOPE model [15] in Geant4 and fluorescent X-ray, particle induced X-ray emission and Auger transition were also considered. Tritium atoms were randomly generated in the gas volume of the cell and decayed to generate beta particles. The kinetic energy of a beta particle generated in this simulation follows the kinetic energy of a tritium beta particle.

The geometry in the previous literature [12] was modified. The simulation geometry is shown in Fig. 1. A cylindrical gas cell made of stainless steel was postulated for this study. Its atomic composition was 70 % iron, 18 % nickel, and 12 % chromium. The gas cell had an inner cylindrical volume to hold the gas medium including tritium. The beryllium window with gold layer as an X-ray window was placed at the end of the inner volume. The gold layer faced the gas volume. The thickness of gold layer was optimized to be 150 nm in previously as described in other literature by the authors [12]. The detector volume (diameter 100 mm) which consisted of a silicon plate with a thin beryllium layer was placed at 1 mm outside of the beryllium window in the gas cell. The photon entered the beryllium layer of detector volume, and its energy was registered in a histogram with a bin width of 100 eV. The energy range of histogram was from 0.5 keV to 20 keV. The histogram of photon energy corresponds to the beta-ray induced X-ray spectrum and it was hereafter denoted as the simulated beta-ray induced X-ray spectrum (s-BIX spectrum). In this simulation, 1×10^8 of tritium decay event were simulated to obtain a s-BIX spectrum. To know s-BIX spectrum for various gas mediums, the inner volume in Fig. 1 was filled with various gases such as hydrogen, nitrogen, oxygen, and rare gases at a given pressure.

3. Results and discussion

3.1. Beta-ray induced X-ray spectrum calculated

Fig. 2 shows the s-BIX spectrum in hydrogen medium at 0.001 atm (1 atm = 101325 Pa). The spectrum was composed of a broad peak from bremsstrahlung and sharp peaks. The bremsstrahlung continuously appeared from 2 keV to 14 keV. The low energy bremsstrahlung below 2 keV disappeared, because the low energy bremsstrahlung was absorbed by the beryllium window of the cell which the thickness was 0.1 mm [12]. The sharp peaks were assigned to the characteristics X-rays from the constituent elements in the simulation

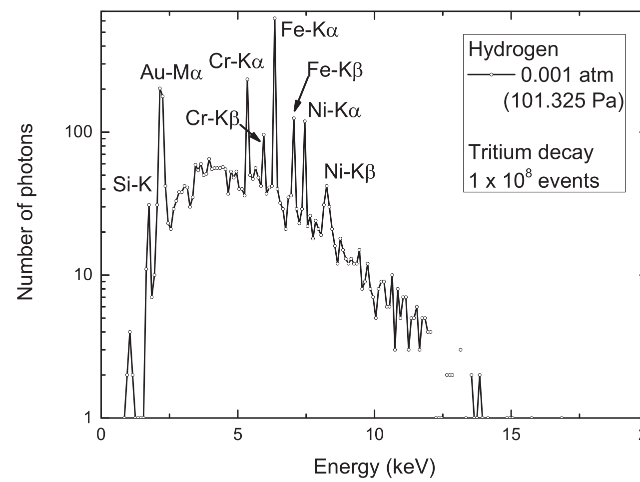

Fig. 2. A typical s-BIX spectrum in hydrogen gas at 0.001 atm with a bin width of 100 eV.

geometry in Fig. 1. The pressure dependence of s-BIX spectrum in hydrogen, nitrogen, and neon are shown in Figs. 3–5. These s-BIX spectra were composed of the bremsstrahlung radiation and the characteristic X-ray peaks. The number of photons at a given energy decreased with increasing gas pressure, whereas the shape of spectrum was nearly same. The total number of photons in s-BIX spectra decreased with increasing pressure of gas medium. Fig. 6 shows s-BIX spectra from argon medium. The bremsstrahlung component in s-BIX spectra of argon decreased as argon pressure increased. On the other hand, the characteristics X-rays of argon appeared at 2.95 keV for Kα and 3.15 keV for Kβ [16] above 0.01 atm. Its intensity increased with increasing argon pressure. The intensity of other characteristics X-rays from constituent elements of cell such as iron, nickel, chromium and gold reduced at higher argon pressure. At 1 atm of argon medium the characteristics X-ray from iron, nickel and chromium almost disappears as seen in Fig. 6. Since the density of argon gas increases as argon pressure increases, the energy of beta particle was consumed in argon gas by an excitation of argon atoms. Fig. 7 shows s-BIX spectra from krypton medium. On the shape of bremsstrahlung above 8 keV, there is no pressure dependence. The characteristics Kr-Kα is scarcely generated by beta particles from tritium decay, because the energy of Kr-Kα is