論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Non-destructive assay technology development using photofission reactions with bremsstrahlung photons for multi-nuclide composition assay in nuclear material
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出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第12235号, 授与年月日:2022年9月22日, 学位の種別:課程博士, 審査員:相樂 洋,小原 徹,千葉 敏,林﨑 規託,片渕 竜也
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第12235号, Conferred date:2022/9/22, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

（博士課程）
Doctoral Program

論 文 要 約

THESIS OUTLINE

系・コース： Department of, Graduate major in	融合理工学 系 原子核工学 コース	申請学位（専攻分野）： Academic Degree Requested	博士 Doctor of (Engineering)
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要約
Thesis Outline

Strengthening the nuclear security is one of the essential issues in the world, and the development of non-destructive assay technologies are strongly demanded to detect the illegal transfer of nuclear material in the export control. One of the important technical challenges is to detect the non-intensive radio-ray emitting nuclear material such as highly enriched uranium, difficult to be measured by passive neutron or photon signals. A non-destructive assay technology was developed using photofission reactions with bremsstrahlung photons to detect the unauthorized nuclear material transfer. High energy photons can penetrate shields easily and the ratio of the photofission reaction by two distinct energies are correlated with the uranium enrichment.

First, the principle of photofission reaction ratio was developed by expanding the interrogating photons to bremsstrahlung photons spectrum to detect highly enriched uranium (HEU) using inverse matrix method. The systematic parameters investigation was carried out based on the electron beam energies of a linear accelerator on bremsstrahlung photons creation at tantalum, and uranium enrichment variation. The incident electron energies of 7.0 and 13.5 MeV were determined based on the photofission reaction peak requirement as well as the neutron measurement noise caused by the (γ, 2n) reaction. Albeit the presence of (γ, 2n) neutron response noise, HEU may be distinguished with a 20 to 30% uncertainty range for 20%EU. Conversely, there may be 10%EU false alert since uranium enrichment uncertainty ranges from 10 to 21%EU at 10% enrichment.

Second, a new numerical methodology was proposed to assay a multi-nuclide system in nuclear material using three distinct mono energy photons and numerical solutions, since the applicability of inverse matrix alone in solving a multi-nuclide system is generally constrained with extremely low accuracy. Ten evaluation cases were conducted with varying isotopic compositions of three nuclides in the thorium fuel cycle with depleted uranium: ^{233}U, ^{232}Th, and ^{238}U. The findings showed good reproducibility, with most cases maintained within a 10% isotopic composition difference. Out of three photon energy combinations investigated, the 6 MeV – 6.5 MeV – 11 MeV displayed the least variation across all ten evaluation cases within 10% composition difference. The result was supported by the sensitivity analysis based on the stochastic error of MCNP where the fittings agree with confidence level above 91.5%.

Third, the developed methodology was applied to detect U-Th multi-nuclide system using bremsstrahlung photons. The systematic parameters investigation was carried out based on the electron beam energies of a linear accelerator on bremsstrahlung photons creation at tantalum, and different nuclide compositions in thorium fuel cycle with depleted uranium – ^{233}U, ^{232}Th, and ^{238}U. Overall, the emergent findings reveal high reproducibility on the 19 incident electron energy combinations simulated with the highest relative composition error of around 0.8 on 7 – 7.5 – 12 MeV and the lowest attainable relative composition error of below 0.02 on 7 – 11 – 13.5 MeV. The relative composition error of 233U ranges from 0.3 to 1.7% across the evaluation cases which are considered to be sufficient for the detection of highly enriched 233U with above 11% enrichment.

Lastly, the measurement system requirement was proposed and deduced with neutron coincidence counting method, distinguishing photofission signal from the background neutron noise caused by bremsstrahlung photon source creation, photo-nuclear reactions by target and surrounded materials, and accidental injection to the neutron detectors. Photofission signal detection based on neutron measurement encounters challenges posed by the background neutrons created from the bremsstrahlung converter target, photon-induced neutrons from target and surrounding materials, and accidental neutron injection to the detector. The neutron measurement system requirement was assessed using coincidence neutron counting method by employing multiple neutron detectors. The photofission-induced neutron signal was evaluated as two order of magnitude higher than the background neutron-induced fission signal, and it was suggested photofission reactions could be quantitatively measured by assuming ideal bremsstrahlung beam collimators to avoid the direct injection of photons or neutrons to detectors. The impact analysis was performed on the measurement possibility with accidental injections of single neutrons coming from mainly background neutron collision in nuclear material, and background neutron reduction requirement and possible neutron absorber designing were finally deduced.

In conclusion, this thesis proposes the use of the developed methodologies to detect HEU or assay the multi-nuclides system in nuclear material for nuclear security. The study has validated the feasibility of high energy bremsstrahlung photons on the PFRR methodology as well as the developed numerical methodology. Last but not least, the measurement system requirement was deduced with neutron coincidence counting method, distinguishing photofission signal from the background neutron noise. For the future experimental demonstration to contribute to the global nuclear security, requirements such as beam current, angle-dependent gamma-ray measurement and reduction of background are concisely discussed and suggested as well.