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(Form 3)

Summary of Doctoral Thesis

TRAN NGUYEN THUY NGAN

Title

Study on Properties of Plastic Scintillators for Designing a Tissue-Equivalent LET Spectrometer

In radiation dosimetry, the absorbed dose D (Gy) which is the total energy absorbed per unit mass can quantify the effect of radiation. However, using D to evaluate the biological damage caused by radiation is inadequate because D does not indicate the specific radiation type. The radiation effects on the human body are normally evaluated by using the equivalent dose H(Sv), which is defined as the product of the absorbed dose D and the quality factor Q given as a function of the linear energy transfer (LET): $H = DQ$. LET (keV/μm) indicates the energy deposited per unit path length (dE/dx) of different radiation types. The quality factor Q varies from 1 to 30 depending on species of radiation and its energy.

Space radiation consists of galactic cosmic rays (GCR), geomagnetic trapped particles, solar energetic particles (SEP) and their secondary particles. The amount of the dose equivalent in space reaches to 1 mSv per day, which is comparable with that received on the ground in one year. The main components of doses in space are primary charged particles (protons and heavy ions) and secondary neutrons produced by the interaction between cosmic rays and the spacecraft materials. Thus, astronauts would face the risk of intense radiation exposure. In addition, the LET of these radiations distributes from 0.2 to 600 keV/μm.

The operation of the high energy accelerators requires the observation and maintenance of radiation safety in the environment around accelerators. Small amounts of radioactivity are generated in the environment of accelerator during its operation, and a mixed radiation field consisting of gamma rays, neutrons and charged particles with a wide range of energies is formed around accelerators. The monitoring of such radiation and radioactivity, as well as the measurement of the radiation dose due to them, are the important task to maintain the radiation protection in accelerator facilities. However, it is normally difficult to measure precisely a small amount of radioactivity produced and contaminated in accelerator environments such as air tunnel, cooling water, and structures of accelerators, or to determine radiation dose of the mixed radiation field. Particularly, there is a little of dosimeters which are usable for mixed radiation as well as some complicated methods using a combination of several detector systems are employed.

Therefore, it is necessary to directly measure the LET of radiation for evaluating *H* in space and accelerator facilities.

Regarding the measurement of radiation dose in space, a Tissue Equivalent Proportional Counter (TEPC) has been used by NASA as a standard space dosimeter. TEPC is a simple gas proportional counter made of tissue equivalent plastics and filled with tissue-equivalent gas. The LET is obtained from the TEPC by assuming that the LET is equal to the lineal energy (the deposited energy divided by the mean chord length of the detector) because position information cannot be given in TEPC. Then, the lineal energy does not represent the LET precisely, and systematic errors of 51 % are the result of this assumption.

RRMD (Real-time Radiation Monitoring Device) is an active detector telescope which utilizes silicon semiconductor detector and others. RRMD has been used as real-time monitoring of space radiation which can achieve the LET distribution, particle count rates, rates of absorbed dose and dose equivalent. However, it is not tissue-equivalent made.

Recently, PS-TEPC (Position Sensitive Tissue Equivalent Proportional Counter) has been developed as a space dosimeter with the property of sensitivity to the position. PS-TEPC is a dosimeter based on LET measurement, which can measure energies and tracks of radiation simultaneously, give us the radiation dose for any kinds of radiation without knowing their species. The detector of PS-TEPC is a time projection chamber (TPC) made of tissue equivalent materials, where a micro pixel chamber (μ-PIC) is used as a two-dimensional position sensor. By using the PS-TEPC, three-dimensional tracks of radiation as well as its energy can be measured, and obtain LET from the measured energy and the track length of radiation. PS-TEPC can be used for radiation dose management onboard the ISS and future manned space missions since it can precisely measure the doses due to various charged particles covered under a wide range of the LET energy spectrum.

An ideal tissue-equivalent dosimeter based on LET measurement should have the following properties: an active (real-time) detector, having sensitivity to detect many radiation types, having the ability to detect the incident position of radiation (position sensitivity), being formed with tissue-equivalent materials, having sensitivity for radiations incident isotropically, being stable and long-lived operation, and having simple structures as possible.

The aim of this study is to examine the properties of PLSs in order to develop a tissue equivalent LET spectrometer. Then, a new dosimetric system based on the LET measurement can be established. This LET spectrometer would give the response to many kinds of radiation and is constructed of materials which are close to water or human tissues. This system offers the potential for using a straightforward method to measure dose equivalent, which differs from existing methods where doses are evaluated only for a known species of radiation.

To obtain the LET value, the deposited energy and path length of radiation in the spectrometer must be measured simultaneously. Thus, for any candidate materials for constructing a LET spectrometer, the material's properties must be examined carefully. For deposited energy information, the response of PLSs radiation must be studied. Besides, for the path length of radiation in the spectrometer, the incidence position, incidence angle of the radiation, and position resolution must be determined.

PLSs are selected as the candidate for constructing a LET spectrometer because of their beneficial properties:

- PLSs are inexpensive materials which have the flexibility in shape and size (cylinders, rods, flat sheets, etc.)
- PLSs have a very rapid decay time constant of about 2 – 3 ns.
- PLSs have the effective atomic number and density similar to those of water and human tissues (because PLSs are composed mainly of hydrocarbon molecules). Thus, plastic scintillators are the potential tissue-equivalent materials for developing a dosimeter.
- PLSs can detect a variety of radiation types (photons, charged particles, and neutrons).

However, PLSs have disadvantages as well:

- The non-proportionality between light yield and deposited energy, especially at low energy region.
- The light yield is affected by quenching effect when irradiated with charged particles.
- The response of PLSs to charged particles shows the particle species dependency at the high value of the specific energy loss dE/dx.

To obtain the LET value, the deposited energy and path length of radiation in the spectrometer must be measured simultaneously. Thus, the response of PLSs to different radiation types as well as the incident position and incident angle of radiation in the spectrometer need to be studied in detail. Additionally, the method for distinguishing output signals from different types of radiation must be established.

In this study, three PLSs EJ-200, EJ-212, EJ-252 ($2''\phi \times 2''$), which are polyvinyl-toluene base, are examined.

The absolute light yield of PLSs is evaluated as W_s which is defined as the average energy required to produce on scintillation photon in a scintillator. The W_s is determined as the result of deposited energy divided by the number of scintillation photon generated in a scintillator. For incident gamma rays, the deposited energy corresponding to the maximum Compton electron (Compton edge).

For incident gamma rays, Compton scattering which is the dominant interaction in PLSs results in a Compton continuum in the energy distribution, hence, the deposited energies are difficult to determine precisely. Then, the response of Compton electrons represents the response of gamma rays. The relative light yield (relative scintillation response) per unit energy deposited by electrons (called as "electron response") of PLSs are examined by using Compton Coincidence Technique.

For determining the deposited energy, an energy resolution is one of the essential factors which must be evaluated, and the light yield is a significant feature in consideration of the energy resolution. In this study, the energy resolution of PLSs is evaluated from the results of the electron response and W_s measurement.

In order to compare energy resolutions, the pulse height distribution for 60-keV gamma rays from an ^{241}Am was measured with the EJ-200 detector. This pulse height distribution corresponds to the photopeak as the result of the interaction between low energy gamma rays with low atomic number materials.

Besides the energy deposition feature, the position sensitivity of PLSs is examined by using square-aligned PLS rods, and multi-segmented photomultiplier tubes (PMTs) are attached to both ends of the rods. By employing signals from both-end PMTs, the possibility of using PLSs for position sensitivity would be confirmed. The measurements using beta and alpha particles were performed, and preliminary data are obtained. Then, a method to determine the incidence position of radiation into the spectrometer, as well as the trajectory of this radiation, can be developed.

The plastic scintillator rod was used to study the response to ions also. The rod was irradiated by heavy ions generated from an accelerator at HIMAC (H – 230 MeV, Si – 800 MeV/u, and C – 400 MeV/u).

Then, the energy resolution of PLSs can also be evaluated by comparing the difference in the energy resolution due to different types of radiation.

Then, the operation principle and the design of a prototype for LET spectrometer is considered and developed.

Form8・Separate Sheet
（様式８・別紙）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏　名　TRAN NGUYEN THUY NGAN

Title
論文題目　Study on Properties of Plastic Scintillators for Designing a Tissue-Equivalent LET Spectrometer

放射線防護を目的とする放射線量測定においては吸収線量とともに、線エネルギー付与 LET (Linear Energy Transfer; 制限付き阻止能 dE/dxΔに等しい。Δは2次電子の上限エネルギー。）の関数である線質係数を測定し、実効線量を評価する必要がある。実際には吸収線量と線質係数の積である線量当量を測定し実効線量を評価することになるが、放射性同位元素が作る通常の放射線場での測定対象放射線はガンマ線やベータ線等であり、それらの線質係数は一定であるので、吸収線量のみを組織等価な物質について測定することにより実効線量を評価できる。吸収線量の測定原理としては電離箱が広く利用されている。一方、宇宙放射線環境や加速器周辺での放射線場は、重イオンや高エネルギー中性子なども含む多様な放射線の場であり、それらの LET は広範にわたるため、線量当量測定のためには LET 測定により線質係数を求める必要がある。
出願者は、入学後に放射線防護と放射線計測を学ぶ過程で、広い範囲の LET を持つ放射線場での線量当量測定が可能な組織等価 LET スペクトロメータの開発に強い興味を持った。組織等価とするためにスペクトロメータの素材としては、生体軟組織または水に密度や原子番号が近く時間応答や感度に優れたプラスチックシンチレータ (PLS) が最適であるが、クエンチングによる発光効率の減少や発光のエネルギーに対する非線形性のため、線量計用の素子としてはほとんど用いられてこなかった。出願者は LET スペクトロメータの設計開発を進めるとともに、プラスチックシンチレータを同スペクトロメータに使用した場合の種々の放射線に対する応答を実験的な研究を詳しく行ない、LET スペクトロメータを製作するうえで不可欠となる、PLS の蛍光効率（Ws）、発光効率のエネルギー依存(電子応答)、エネルギー分解能、イオンに対する応答、照射位置依存性などこれまでほとんど測定されてこなかった PLS の基礎的特性の実験的把握を行った。
博士論文は6章からなる。第1章では宇宙放射線環境や加速器放射線環境など幅広い粒子種とエネルギーの放射線を扱う場合の実効線量測定における LET 測定の必要性および PLS を選定した理由について記述している。第2章は PLS の放射線検出原理、温度依存、放射線損傷、発光量および LET スペクトロメータの先行研究についての文献調査結果である。第3章では、本論文の主題である PLS の種々の基礎特性の実験方法について論じている。これまでの無機シンチレータの Ws の測定では、光電子増倍管での増幅を行わない光ダイオードモード(PD)測定という技法が用いられていた。しかし、PLS は発光量が無機シンチレータに比べて発光量が少なく、PD 測定技法を用いることができないという問題があった。そこで出願者は、予め無機シンチレータからのシンチレーション光を、PD モードと光電子増倍管の通常モードで測定し、光電子増倍管での増幅率を求めておき、同じ光

電子増倍管を通常モードで用いて PLS からのシンチレーション光を測定することにより、その Ws 値を得るという技法を開発した。また、種々の RI からのガンマ線を PLS で散乱させ、散乱光子を NaI または Ge 検出器で検出して、PLS からの信号との同時計測を行い、NaI または Ge 検出器の方向への散乱のみを測定する技法を用いて、電子応答およびその分解能を測定する技法を述べている。
第 4 章でその結果をまとめている。3 種類の PLS（EJ-200, 212, 252）に対して、それぞれ 104±9, 93±8, 146±13 という Ws 値(eV)を得ている。また、同じく 3 種類の PLS に対して 30 keV-470 keV の範囲での電子に対する光収率を測定し最大 50%の減少を確認している。さらに同じエネルギー範囲でのエネルギー分解能を系統的に得た。これらには PLS の利用において極めて重要な基礎データである。さらに、LET スペクトロメータを設計する際の基礎的なデータとして、両端に光電子増倍管を付けた棒状のプラスチックシンチレータの種々の場所に α 線や β 線を入射した場合の、光電子増倍管の出力比を測定している。さらに数 100MeV の H イオン、C イオンおよび Si イオンを入射した場合の PLS でのエネルギー損失とその幅を測定している。第 5 章では、前章までで得られた PLS の基礎特性を踏まえ、PLS を利用した LET スペクトロメータの設計について論じている。高エネルギー放射線が LET スペクトロメータを貫通することを想定し、入射位置と出射位置から放射線の通過距離を求め、エネルギー付与と通過距離の比から LET を得る。LET の測定精度は、前章で求めた位置分解能およびエネルギー分解能によって決まる。
PLS の Ws 及び電子応答の実験結果については、すでに英文の学術雑誌に投稿し掲載されている。また PLS の電子応答における分解能や入射位置依存性に関わる実験結果については複数の国際会議で発表を行っている。審査における発表、質疑応答は英語でなされ、英語に関する能力は十分と判断された。以上の理由により、審査会は、本論文が学位の授与に値すると全員一致で判断した。