学位論文内容の要旨
（Abstract of thesis）

博士の専攻分野の名称　　博士（医理工学）　　氏 名　ゾルバダラル ツォードル
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学 位 論 文 題 名
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Production of medical radioisotopes ^{68}Ga and ^{45}Ti in deuteron-induced reactions in cyclotrons
(サイクロトロンを用いた重陽子入射反応による医療用放射性同位元素 ^{68}Ga と ^{45}Ti の生成)

Positron Emission Tomography (PET) is a powerful nuclear imaging technique based on an annihilation reaction of a positron and an electron. A positron emitted from a radiopharmaceutical injected into a patient reacts with an electron in tissue and decays into two 511-keV gamma rays. The positron emitter contained in the radiopharmaceutical is essential for the imaging technique. A variety of positron emitters can be used, and their production is worth investigation.

The dominant method to produce the positron emitters is charged-particles-induced reactions in cyclotrons. Generators and neutron-induced reactions can also produce a few positron emitters. Although most PET isotope production routes are well established, there is still a need for continuous research and development for better route and more efficient radionuclides. Nuclear reaction data are required for such research and development. Based on the nuclear reaction data, we can select projectile and targets and optimize the projectile energy to maximize the yield of the desired product and to minimize co-produced impurities.

Positron emitters ^{68}Ga and ^{45}Ti are expected to become more popular in clinical PET scanners. Their promising production routes can be considered as the (p,n) reactions on isotopically enriched targets of ^{68}Zn and ^{45}Sc. Alternative production routes are the (d,2n) reactions on ^{68}Zn and ^{45}Sc. In the literature, a few experimental cross section data on deuteron-induced reactions for production of ^{68}Ga and ^{45}Ti were reported. In addition, there are significant discrepancies among them. Therefore, we aimed to investigate the deuteron-induced reactions to produce ^{68}Ga and ^{45}Ti to investigate the production routes.

The production cross sections of deuteron-induced reactions on natural zinc for ^{68}Ga and on scandium for ^{45}Ti were measured up to 24 MeV, respectively. The measured excitation functions were compared with previous experimental data and the theoretical model calculation of the TENDL library. The physical yields for ^{68}Ga and ^{45}Ti production were deduced from the measured cross sections and compared with previous experimental data.

Two experiments were carried out to measure reliable data on the production cross sections of ^{68}Ga and ^{45}Ti in deuteron-induced reactions on natural zinc and scandium. The two experiments were performed at the AVF cyclotron of RIKEN RI Beam Factory. Stacked-foil activation technique and γ-ray spectrometry were used to measure the cross sections. Two stacked targets were prepared and irradiated with deuteron beams. The incident beam energies were measured by the time-of-flight method. The energy degradation in the stacked foils was calculated using the SRIM code. The beam intensities were measured by Faraday cups and cross-

checked using the $^{nat}Ti(d,x)^{48}V$ monitor reaction. γ-ray spectra of the irradiated foils were measured by high-resolution HPGe detectors without chemical separation. The detectors were calibrated by a standard mixed multiple γ-ray emitting point source.

For the ^{68}Ga experiment, the stacked target was composed of metallic foils of ^{nat}Zn (17.64 mg/cm^2, 99.9% purity) and ^{nat}Ti (9.13 mg/cm^2, 99.6% purity). The target was irradiated for 22 min by a 24-MeV deuteron. The measured beam intensity was corrected to 102.4 nA by increasing 6.6% from the measured value according to comparison of the monitor reaction. The distance between the detector and the foils was chosen to keep the dead time less than 7%.

The excitation functions of the $^{nat}Zn(d,x)^{68}Ga$ reaction were measured up to 24 MeV. Production cross sections of co-produced radioisotopes $^{65,66,67}Ga$, $^{63,65,69m}Zn$, ^{61}Cu and ^{58}Co were also determined. The derived excitation function of the $^{nat}Zn(d,x)^{68}Ga$ reaction is consistent with the data of Šimečková et al. (2017). The deduced physical yield of ^{68}Ga partially agrees with the previous data. The yields of proton- and deuteron-induced reactions on ^{68}Zn for ^{68}Ga production are compared. The yield of the $^{68}Zn(d,2n)^{68}Ga$ reaction is found to be comparable with that of the $^{68}Zn(p,n)^{68}Ga$ reaction. The data obtained in this work are useful to consider the best reaction to produce ^{68}Ga for practical use.

For the ^{45}Ti experiment, the stacked target consisted of metallic foils of ^{45}Sc (7.71 mg/cm^2 thickness, 99.0% purity and 76.0 mg/cm^2 thickness, 99.0% purity), ^{27}Al (4.99 mg/cm^2, 99.6%) and ^{nat}Ti (9.13 mg/cm^2, 99.6%). The target was irradiated for 30 min with a 24-MeV deuteron beam. Based on comparison of the monitor reaction, the intensity was corrected to 175.2 nA by decreasing 3% from the measured value (180.3 nA). The dead time was kept below 7% in the measurements.

The excitation functions for the production of ^{45}Ti and co-produced radioisotopes such as ^{44}Ti and $^{44g44m,46}Sc$ was measured up to 24 MeV. The derived excitation function of the $^{45}Sc(d,2n)^{45}Ti$ reaction is consistent with the earlier published data of Hermanne et al. (2012). The deduced physical yield of ^{45}Ti is slightly larger than the previous experimental data. The radioactive-contamination-free ^{45}Ti can be obtained via the $^{45}Sc(d,2n)^{45}Ti$ reaction in the energy region of 15 - 8 MeV applying chemical separation.

In conclusion, we investigated the deuteron-induced reactions on natural zinc and scandium. The production cross sections of ^{68}Ga and ^{45}Ti were determined. Based on the results, the deuteron-induced reactions on enriched ^{68}Zn and natural scandium can be alternative routes for cyclotron production. The data measured in these experiments extend the nuclear reaction database and are available for optimizing production routes of the medical isotopes.