Development of RF carpet gas cell for extracting ^{229m}Th ions

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The first excited state of a ^{229}Th nucleus (^{229m}Th) has an excitation energy of ∼8.3 eV.[1,2] Because this is close to the binding energy of the valence electrons, decay modes of ^{229m}Th [internal conversion (IC), electronic bridge (EB) transitions, and γ-ray emission] may vary depending on the chemical environment. However, EB transitions and γ-ray emission of ^{229m}Th have never been observed, because the IC process dominantly occurs in most chemical environments in which electron biding energies are below 8 eV. Examples in which the IC process is inhibited are ^{229m}Th ions trapped in vacuum. The trapping of $^{229m}Th^{2+}$ and $^{229m}Th^{3+}$, which have high ionization energies (18.3 and 28.65 eV, respectively), may lead to γ-ray emission. Moreover, because the electron transition energies in a Th^{+} ion are close to 8 eV, the trapping of $^{229m}Th^{+}$ may allow occurrence of an EB transition, which is an unknown high-order decay mode along with the transition of an occupied orbital electron to an unoccupied orbital and the emission of a photon. Observing such decay modes requires the extraction of numerous ^{229m}Th ions to an ion trap. In this study, we fabricated a radiofrequency (RF) carpet gas cell to efficiently extract ^{229m}Th ions recoiling out of a ^{233}U source. Moreover, we optimized and evaluated the device by extracting ^{220}Rn ($T_{1/2}$ = 55.6 s) and ^{216}Po ($T_{1/2}$ = 0.144 s) ions emitted from a ^{224}Ra source under the recoil energy of an α decay.

Figure 1 shows a photograph and schematic of the developed gas cell. The ions emitted from a source placed inside the gas cell are decelerated by He gas, pushed toward an RF carpet by a positive (push) voltage, and transported to the central hole of the RF carpet using the RF surfing technique.[3] Subsequently, the ions are guided to high vacuum by a quadrupole ion guide (QPIG). The ions with a specific mass-to-charge ratio (m/z) are separated by a quadrupole mass separator (QMS) and guided to a channeltron detector. The vacuum chamber consists of conflat flanges, and it is baked to reach a base pressure of $\sim 1 \times 10^{-7}$ Pa, to ensure that the amount of impurities emitted from the gas cell is small. Thus, the neutralization or molecularization of ions by impurities is minimized. Because of the relatively small recoil energy of an α decay (∼100 keV), we shortened the length of the gas cell to 10 cm compared to that of the gas cell we developed for the study of superheavy elements (26 cm).[3]

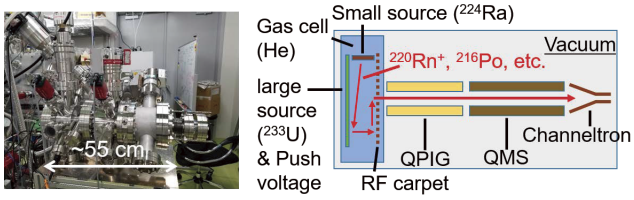

Fig. 1. Photograph (left) and schematic (right) of developed RF carpet gas cell.

We investigated the conditions under which the extraction efficiency is maximum, by extracting $^{216}Po^{+}$ ions emitted from a thin ^{224}Ra source[3,4] (∼400 Bq) placed inside the gas cell. The counts of $^{216}Po^{+}$ ions measured by the channeltron detector reached maximum when the push voltage of the RF carpet was from +5 V to +90 V, the offset voltage of the RF carpet was +4 V (He 10 mbar) and +10 V (He 15 mbar), the RF voltage of the RF carpet was 217 Vpp (15.43 MHz), the audiofrequency voltage of the RF carpet was 2.6 Vpp (200 kHz), the DC voltage of the QPIG was +1 V, and the RF voltage of the QPIG exceeded 106 Vpp.

We measured the mass spectrum of the ions emitted from the ^{224}Ra source under the above-mentioned conditions. In Fig. 2, the peaks of $^{220}Rn^{+}$, $^{216}Po^{+}$, $^{212}Pb^{+}$, $^{208}Pb^{+}$, and $^{208}Tl^{+}$ are noticeable. Only when He gas introduced in the gas cell is purified using purifiers (SAES PS3-MT3-R-1 and MC1-902F), the peaks of $^{216}Po^{2+}$, $^{212}Pb^{2+}$, $^{208}Pb^{2+}$, and $^{208}Tl^{2+}$ are observed. Thus, when $^{229m}Th^{2+}$ and $^{229m}Th^{3+}$ ions are needed, gas purification should be conducted.

We measured the absolute maximum extraction efficiency of $^{220}Rn^{+}$ as the ratio of the number of extracted $^{220}Rn^{+}$ to that of $^{220}Rn^{+}$ emitted from the ^{224}Ra source.[3] The former was determined from the alpha-decay events of ^{220}Rn detected by the channeltron (the counts increased during extraction and decayed after stopping the extraction with a half-life of 55.6 s). The extraction efficiency was 16(2)% at He 10 mbar and 20(1)% at He 15 mbar with purified He

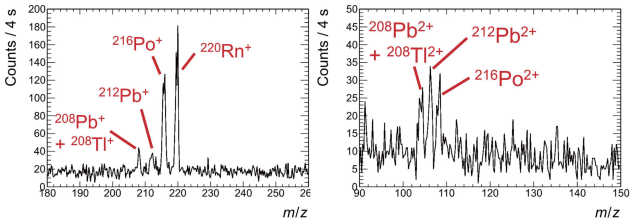

Fig. 2. Mass spectra of ions extracted from ^{224}Ra source without (left) and with (right) He gas purification.

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gas. Hence, using a ^{233}U source with a diameter of 90 mm and a radioactivity of 100 kBq would enable extracting ^{229m}Th ions at a rate of $\sim$400 s^{-1}, which is sufficiently high to observe γ-ray emission and EB transitions using photomultipliers.

References

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