First successful ionization of lawrencium by surface ionization process

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The first ionization potential (IP) is one of the fundamental physical and chemical properties of an element. It directly reflects the electronic configuration of the element. The relativistic effects affect the electronic configuration and would be noticeable for the heaviest elements. With an experimentally determined IP value of heavy elements, therefore, we can contribute to a better understanding of shell effects and how relativistic effects play a role in the electronic structure of heavy atoms. The ground-state electronic configuration of the heaviest actinide, lawrencium (Lr, the atomic number Z = 103), is predicted to be [Rn]5f^{14}7$s^2$7$p_{1/2}$, which is different from that of the lanthanide homolog lutetium (Lu) [Xe]4f^{14}6$s^2$5d. The reason for this change in the ground-state configuration is that the 7p orbital of Lr is stabilized below the 6d orbital by strong relativistic effects [1]. The weakly-bound outermost electron results in a significantly lower IP of Lr as compared with its neighboring heavy actinides [2]. However, the elements heavier than fermium (Fm, Z = 100) are produced at accelerators using reactions of heavy ions with heavy target materials. Moreover, both half-lives and production cross sections of the isotopes of the still heavier elements are rapidly decreasing. Thus, they are usually available in quantities of a few atoms at a time. Consequently, beginning with about the end of the actinides, properties of the heaviest elements must be studied on an atom-at-a-time scale. The IP values of the heavier actinides with Z > 100, therefore, have not been measured using well-established methods.

The surface ionization is a process in which an atom is ionized via the interaction with a solid (metal) surface at high temperature. The ionization yield depends on the surface temperature of the solid material, a work function and the ionization potential of the element of interest. In order to determine the IP value based on the surface ionization process at the atom-at-a-time scale, we have developed a surface ionization type ion-source as part of the JAEA-ISOL (Isotope Separator On-Line) setup, which was coupled to a He/CdI_2 gas-jet transport system [3]. As the first step to the determination of the IP value of Lr, we conducted ionization and mass-separation of a short-lived Lr isotope with the ion-source and the ISOL system.

The isotope ^{256}Lr ($T_{1/2}$ = 27 s) was produced in the reaction of ^{249,250,251}Cf(^{11}B, xn)^{256}Lr [4]. A ^{249,250,251}Cf target was irradiated with a 67.9-MeV ^{11}B beam from the JAEA tandem accelerator. For comparison, the lutetium isotopes ^{168m}Lu and ^{168g}Lu, with half-lives of 6.7 min and 5.5 min, respectively, were also synthesized in the ^{162}Dy(^{11}B, 5n) reaction. The nuclear reaction products recoiling from the targets were transported to the ion-source by a He/CdI_2 gas-jet transport system. The products were ionized in the ion-source, accelerated with 30 kV, and mass-separated with a mass-separator in ISOL. The amount of ions collected at the end of the ISOL after mass-separation was determined by α-particle or γ-ray measurements. To calculate ionization efficiencies, nuclear reaction products transported from a target recoil chamber were collected directly and measured in advance of the ionization experiments. To compare the ionization efficiencies on different surface materials of the ion-source, a rhenium (Re) surface and a tantalum (Ta) surface were employed in this study.

An α-particle spectrum of ions ionized on the Re surface and mass-separated with mass number A = 256 is shown in Fig. 1. Alpha-particles originating from ^{256}Lr and its decay products, ^{256}No and ^{252}Fm, are clearly observed. This result unambiguously demonstrates that we have successfully ionized and mass-separated ^{256}Lr for the first time, verifying the surface ionization ion-source is a promising tool for the measurement of IP values of single atoms. The ionization efficiencies of Lr and Lu on the Re surface were 42^{+20}_{-19}% and 19.9 ± 7.0%, respectively. In the case of the Ta surface, the efficiency of Lr was 19^{+9}_{-8}% while that of Lu was 4.0 ± 1.4%. The ionization efficiencies of Lr on both the surfaces were higher than those of Lu. The results suggest that the IP of Lr should be lower than that of Lu. This is consistent with the theoretical prediction from a coupled cluster calculation that takes into account relativistic effects [2]. Using the present system, the ionization efficiency of Lr is being examined in more details for the determination of its IP value.

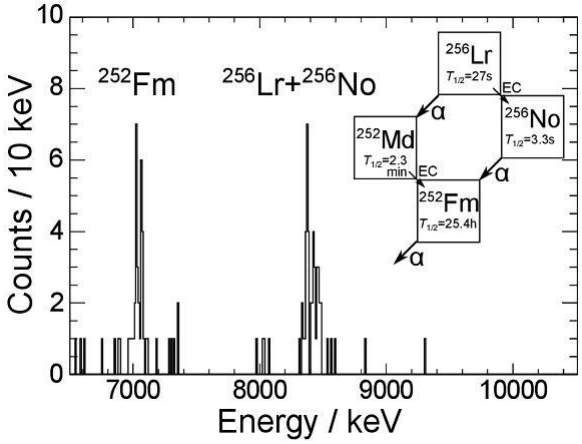

Fig.1 Measured α-particle spectrum of mass-separated ions with mass number A = 256 with the Re surface.

References

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