Production Cross Sections of ^{261}Rf and ^{262}Db in Bombardments of ^{248}Cm with ^{18}O and ^{19}F Ions

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The transactinide nuclei, ^{261}Rf and ^{262}Db, have been produced in the ^{248}Cm(^{18}O, 5n) reaction at beam energies of 91, 94, and 99 MeV, and in the ^{248}Cm(^{19}F, 5n) reaction at 106 MeV, respectively. The production cross sections are evaluated from the mother-daughter correlations of α energies between ^{261}Rf and ^{257}No, and ^{262}Db and ^{258}Lr. The maximum cross section of the ^{248}Cm(^{18}O, 5n) reaction is measured to be 13 ± 3 nb at around 94 MeV, while the production cross section of ^{262}Db in ^{248}Cm(^{19}F, 5n) is 1.3 ± 0.4 nb at 106 MeV.

1. Introduction

For chemical studies of element 104, 78-s ^{261}Rf produced in the ^{248}Cm(^{18}O, 5n) reaction at 97 MeV with a cross section of 5 nb[1] has been used. The relative maximum cross section in the above reaction, however, was obtained at the vicinity of 95-MeV ^{18}O bombarding energy.[2] On the other hand, the cross section of <0.9 nb at 94.2 MeV has been recently measured.[3] In the chemical study of element 105, 34-s ^{262}Db and partially 27-s ^{263}Db produced in the 5n- and 4n reactions of ^{18}O with ^{249}Bk targets with cross sections of 6 nb and 2 nb,[4] respectively, are used, although the target material ^{249}Bk is very rare and highly radioactive with the half-life of 320 d. Thus the other reaction path ^{248}Cm(^{19}F, 5n) producing ^{262}Db has been studied as a possible alternative. Recently, the production cross section at a beam energy of 106.5 MeV has been measured to be 0.26 nb by Dressler et al.,[5] which is more than one order of magnitude smaller than that in the ^{249}Bk(^{18}O, 5n)^{262}Db reaction,[4] while Naour et al. have reported the relatively large cross section value of about 2 nb in the same reaction.[6]

In the present study, to evaluate the optimum irradiation condition for the production of ^{261}Rf through the ^{248}Cm(^{18}O, 5n) reaction, the production cross sections at 91, 94, and 99 MeV are measured. We also determine the accurate production cross section of ^{262}Db in the bombardment of ^{248}Cm with the 106-MeV ^{19}F beam.

2. Experimental Procedures

A schematic of the experimental setup including a target and recoil chamber arrangement and a rotating wheel detection system is shown in Figure 1. The ^{248}Cm target of 590 μg/cm^2 thickness and 5 mm diameter was prepared by electrodeposition onto a 2.2 mg/cm^2 thick Be backing foil. The $^{18}O^{6+}$ and $^{19}F^{7+}$ beams from the JAERI tandem accelerator passed through a 2.0 mg/cm^2 HAVAR entrance window, 0.09 mg/cm^2 He cooling gas, and the 2.2 mg/cm^2 Be target backing before entering the target material. The beam current of each ion was approximately 250–300 particle nA.

The reaction products recoiling out of the target were stopped and thermalized in a volume of He gas (about 1 bar) which had been loaded with KCl aerosols generated by sublimation from the surface of KCl powder at 620 °C. The products attached to the aerosols were swept out of the recoil chamber with the He gas (2.0 L/min) and were transported through a Teflon capillary (2.0 mm i.d.) to the rotating wheel detection system MANON (**M**easurement system for **A**lpha-particle and spontaneous fissio**N** events **ON** line), where they were deposited on polyethylene terephthalate foils of 120 μg/cm^2 thickness and 20 mm diameter at the periphery of an 80-position stainless steel wheel of 80 cm diameter. The wheel was periodically rotated to position the foils between six pairs of Si PIN photodiodes for α-particle detection. Each detector had an active area of 18 × 18 mm^2. The detection efficiency of approximately 40% for α particles was achieved. The energy resolution (FWHM) was about 30 keV for the top detectors and was 100 keV for the bottom ones.

To determine the gas-jet transport yield, we first collected

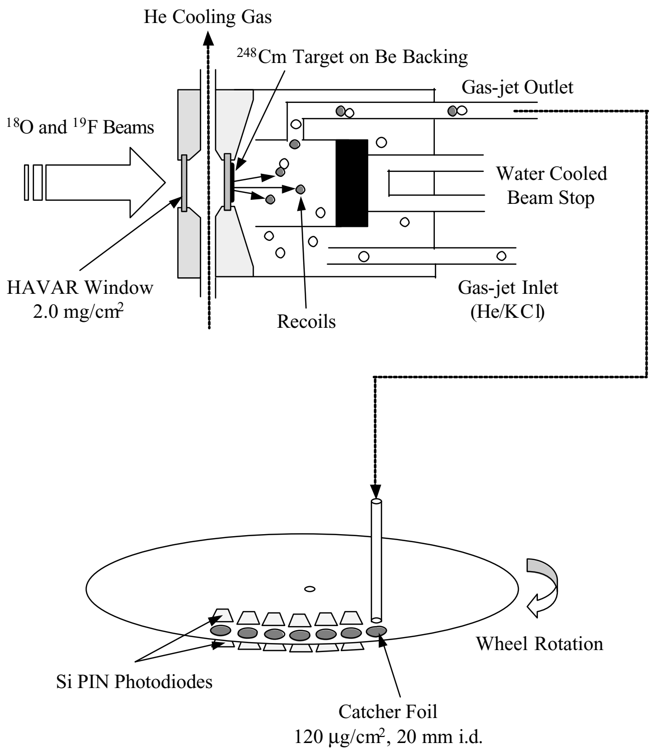

Figure 1. Schematic of the experiment for the production of ^{261}Rf and ^{262}Db.

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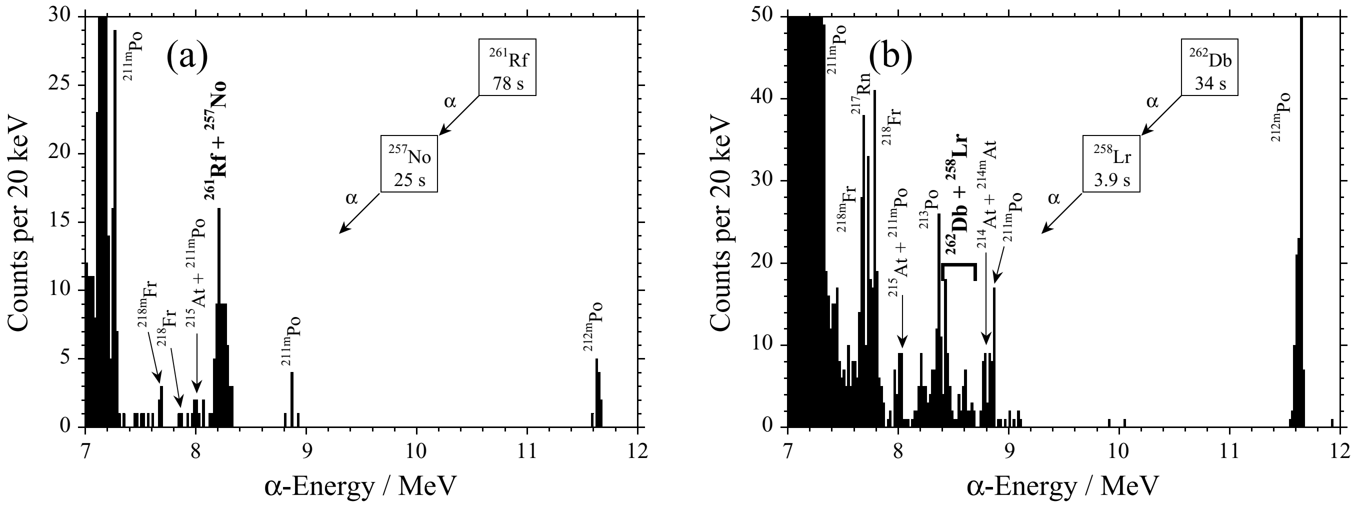

Figure 2. (a) Sum of α-particle spectra measured in the bombardment of the ^{248}Cm target with 94 MeV ^{18}O ions, and (b) that with 106-MeV ^{19}F ions.

TABLE 1: Experimental production cross sections of ^{261}Rf and ^{262}Db produced in the ^{248}Cm(^{18}O, 5n) and ^{248}Cm(^{19}F, 5n) reactions, respectively, and those in the other reactions.

Reaction	E_{lab} / MeV	σ / nb	Reference
^{248}Cm(^{18}O, 5n)^{261}Rf	97	5	1
^{248}Cm(^{18}O, 5n)^{261}Rf	94.2	<0.9	3
^{248}Cm(^{18}O, 5n)^{261}Rf	100.4	$4.5^{+3.5}_{-2.0}$	3
^{248}Cm(^{18}O, 5n)^{261}Rf	103.9	$1.7^{+3.3}_{-1.0}$	3
^{248}Cm(^{18}O, 5n)^{261}Rf	91	8 ± 2	Present
^{248}Cm(^{18}O, 5n)^{261}Rf	94	13 ± 3	Present
^{248}Cm(^{18}O, 5n)^{261}Rf	99	8 ± 2	Present
^{244}Pu(^{22}Ne, 5n)^{261}Rf	114	4.4	16
^{244}Pu(^{22}Ne, 5n)^{261}Rf	120	3.8	16
^{248}Cm(^{19}F, 5n)^{262}Db	106.5	$0.26^{+0.15}_{-0.09}$	5
^{248}Cm(^{19}F, 5n)^{262}Db	106	2	6
^{248}Cm(^{19}F, 5n)^{262}Db	106	1.3 ± 0.4	Present
^{249}Bk(^{18}O, 5n)^{262}Db	99	6 ± 3	4

the recoil of ^{252}Md ($T_{1/2} = 2.3$ min) produced in the reaction ^{238}U(^{19}F, 5n)^{252}Md behind the target in an Al catcher foil to get a reference value (100%), while ^{252}Md transported in the jet was collected on a glass filter. ^{252}Fm ($T_{1/2} = 25$ h), the EC decay daughter of ^{252}Md, in both samples was chemically separated and subjected to α spectrometry. By comparing the production rate measured after transport through the jet with the absolute production rate from the catcher foil, the transport efficiency was determined to be approximately 35%. The production cross sections were evaluated from the mother-daughter (α-α) correlations for ^{261}Rf–^{257}No and ^{262}Db–^{258}Lr.

3. Results and Discussion

The sum of α-particle spectra measured in the six top detectors for the production of ^{261}Rf at 94 MeV is shown in Figure 2(a). In the α-energy range of 8.10–8.40 MeV, α lines from 78-s ^{261}Rf (8.28 MeV) and its daughter 26-s ^{257}No (8.22, 8.27, and 8.32 MeV) are clearly seen. No contributions from other nuclides in this energy window are observed, although there exist several α lines originating from the transfer reaction products from the Pb impurity in the ^{248}Cm target. A total of 166 events were registered both in the top and bottom detectors in the singles measurement and 57 α-α correlation events were detected at 94 MeV. Assuming a 100% α-decay branch (I_α) for both ^{261}Rf and ^{257}No, the production cross sections of ^{261}Rf in this reaction were evaluated to be 8 ± 2, 13 ± 3, and 8 ± 2 nb at the ^{18}O beam energies of 91, 94, and 99 MeV, respectively, as shown in Table 1. The contribution of the direct production of ^{257}No via the ^{248}Cm(^{18}O, α5n) reaction is assumed to be negligible in the studied energy region. The present cross section values are in good

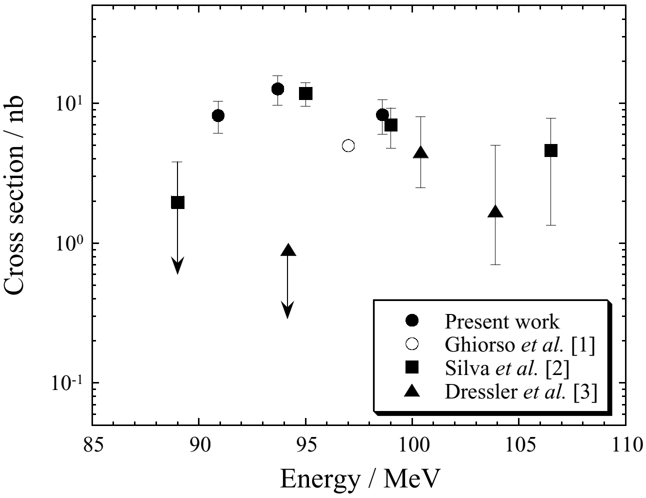

Figure 3. Cross sections of the ^{248}Cm(^{18}O, 5n)^{261}Rf reaction as a function of the ^{18}O bombarding energy. The data taken from the literature[1–3] are also shown.

agreement with that of about 5 nb at around 97 MeV by Ghiorso et al.[1]

Figure 2(b) shows the sum of α-particle spectra measured in the six top detectors in the 106 MeV ^{19}F-induced reaction of ^{248}Cm. The α lines corresponding to those of 34-s ^{262}Db and its daughter 3.9-s ^{258}Lr are observed. 19 mother-daughter correlations of α energies between ^{262}Db (8.45, 8.53, and 8.67 MeV) and ^{258}Lr (8.565, 8.595, 8.621, and 8.654 MeV) were detected. With assumption of $I_\alpha = 64\%$ in ^{262}Db and $I_\alpha = 100\%$ in ^{258}Lr (Ref. 7), the production cross section of ^{262}Db was evaluated to be 1.3 ± 0.4 nb. The present cross section value is larger by a factor of about 6 than that by Dressler et al.,[5] while that is nearly equal to the value of about 2 nb reported by Naour et al.[6]

In Figure 3, the measured cross sections are plotted as a function of the ^{18}O bombarding energy together with the literature data,[1–3] where the relative cross section values in Reference 2 are normalized to the present results. The data except for the value <0.9 nb at 94.2 MeV in Reference 3 are smoothly connected with the maximum cross section of about 13 nb at around 94 MeV and show a slight tail in the energy region beyond 100 MeV.

The experimental cross sections were compared with those expected from statistical model calculations with the HIVAP code[8] which has been modified for the calculations of fusion cross sections.[9] The coupled channel method with the CCDEF code[10] was used for the calculation of the fusion cross sections, in which the influence of the static deformation of the colliding nuclei as well as the inelastic coupling to collective excited levels was considered. In the present calculations, the deformation of β_2 and β_4[11] of the ^{248}Cm nucleus was taken into account and the inelastic coupling to the 2^+ and 3^- states of ^{18}O, and to that of 3^- in ^{248}Cm were considered. No coupling calculations for ^{19}F were performed. The fusion cross section values were input to the HIVAP calculations as were the initial spin distributions of the compound nucleus. The evaporation residue cross sections were calculated by the conventional Γ_n/Γ_f competition method, where Γ_n and Γ_f mean the decay widths for neutron evaporation and fission, respectively. A brief description for the deexcitation process is given in the following. The level density at the ground state as well as the saddle point state for a given excitation energy E was calculated by

$$\rho(E) = K_{\rm vib} K_{\rm rot} \rho_{\rm int}(E), \tag{1}$$

where $K_{\rm vib}$ and $K_{\rm rot}$ are the coefficients for rotational and vibrational enhancements of non-collective internal nuclear excitations $\rho_{\rm int}(E)$.[12] To evaluate $K_{\rm vib}$ and $K_{\rm rot}$, the ground state quadrupole deformation β_2 was taken from Reference 11, while the saddle-point deformation was from Reference 13 in the present calculations. The fission barrier height B_f was given by $B_{\rm RLDM} - \delta W$, where the rotating liquid drop fission barrier $B_{\rm RLDM}$ was obtained from Reference 13. The shell correction energy δW was calculated as, $\delta W = M_{\rm exp} - M_{\rm LDM}$ using the experimental masses $M_{\rm exp}$[14] and the liquid drop model masses $M_{\rm LDM}$.[15]

The maximum cross section of 10 nb at 96 MeV was calculated with the statistical model HIVAP code for the ^{248}Cm(^{18}O, 5n) reaction, while the calculated cross section in ^{248}Cm(^{19}F, 5n) was 1.5 nb at 106 MeV, indicating that good agreement with the present experimental values was obtained in both reactions.

Table 1 summarizes the experimental production cross sections of ^{261}Rf and ^{262}Db together with the reference values.[1,3–6,16] In the case of the production of ^{261}Rf, the cross section in the ^{248}Cm(^{18}O, 5n) reaction is larger by a factor of 3 than that in ^{244}Pu(^{22}Ne, 5n),[16] while the production cross section of ^{262}Db in the ^{249}Bk(^{18}O, 5n) reaction[4] is larger than that in ^{248}Cm(^{19}F, 5n). It is clear that the more mass-asymmetric reaction system gives the larger production cross section.

In Figure 4, the cross sections observed in the ^{248}Cm(HI, 5n) reactions are plotted as a function of atomic number of the products. The literature values are taken from ^{248}Cm(^{12,13}C, 5n),[17] ^{248}Cm(^{15}N, 5n),[18] ^{248}Cm(^{18}O, 5n),[1] ^{248}Cm(^{19}F, 5n),[5,6] and ^{248}Cm(^{22}Ne, 5n).[19] The decrease of the cross section with increasing atomic number is obvious. The extrapolation of the production cross section for element 108, ^{269}Hs produced in the ^{248}Cm(^{26}Mg, 5n) reaction, gives approximately a few pb.

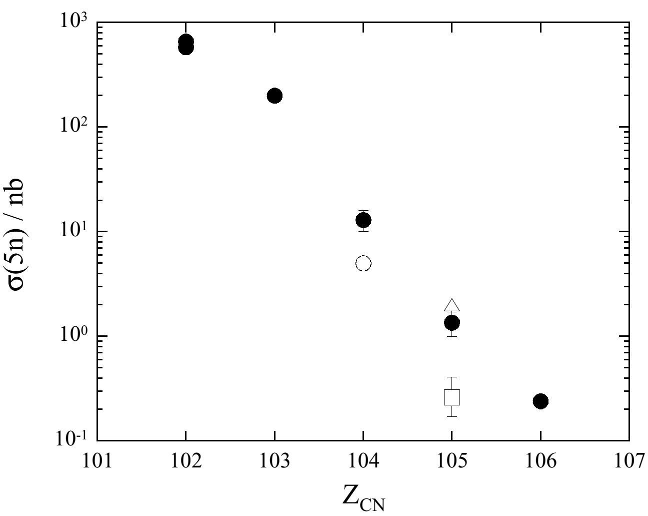

Figure 4. Cross sections for heavy elements produced in the ^{248}Cm(HI, 5n) reactions. The present results together with those for the ^{248}Cm(^{12,13}C, 5n),[17] ^{248}Cm(^{15}N, 5n),[18] ^{248}Cm(^{18}O, 5n),[1] ^{248}Cm(^{19}F, 5n),[5,6] ^{248}Cm(^{22}Ne, 5n)[19] reactions are shown.

4. Conclusions

The transactinide nuclei, ^{261}Rf and ^{262}Db, were produced in the ^{248}Cm(^{18}O, 5n) reaction at 91, 94, and 99 MeV, and in the ^{248}Cm(^{19}F, 5n) reaction at 106 MeV, respectively. The newly developed rotating wheel detection system, MANON, was used to detect α-α correlations between ^{261}Rf and ^{257}No, and ^{262}Db and ^{258}Lr. The production cross section of ^{261}Rf was determined to be 13 ± 3 nb at 94 MeV, while that of ^{262}Db was 1.3 ± 0.4 nb. The statistical model calculations coupled with the coupled channel code CCDEF taking into account the deformation of the colliding nuclei as well as the coupling to the inelastic channels well reproduced the experimental cross sections.

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