

Study of Heavy-ion Induced Fission for Heavy Element Synthesis

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Fission fragment mass distributions were measured in heavy-ion induced fission of ^{238}U . The mass distributions changed drastically with incident energy. The results are explained by a change of the ratio between fusion and quasifission with nuclear orientation. A calculation based on a fluctuation dissipation model reproduced the mass distributions and their incident energy dependence. Fusion probability was determined in the analysis. Evaporation residue cross sections were calculated with a statistical model for the reactions of $^{30}\text{Si}+^{238}\text{U}$ and $^{34}\text{S}+^{238}\text{U}$ using the obtained fusion probability in the entrance channel. The results agree with the measured cross sections of $^{263,264}\text{Sg}$ and $^{267,268}\text{Hs}$, produced by $^{30}\text{Si}+^{238}\text{U}$ and $^{34}\text{S}+^{238}\text{U}$, respectively. It is also suggested that sub-barrier energies can be used for heavy element synthesis.

I. INTRODUCTION

Experiments to produce superheavy nuclei (SHN) have been carried out by using heavy-ion fusion and evaporation reactions [1–3]. Prediction of the cross sections for SHN is important to make an experimental plan. The reaction proceeds in three steps; (1) penetration of the Coulomb barrier between two colliding nuclei (capture), (2) formation of a compound nucleus after nuclear contact (3) survival of the excited compound nucleus by particle evaporation against fission (fusion-fission). The first step, penetrating the Coulomb barrier, is relatively well understood. Survival probability of compound nucleus can be calculated in a statistical model. The second process, forming a compound nucleus (fusion probability), is not well understood, and it is the subject of this research program.

We have studied the reaction using actinide target nuclei. These reactions are especially important because more neutron rich SHN can be produced than when using cold fusion reactions, thus decay properties of these nuclei have information on the structure in the vicinity of spher-

ically closed-shell at $N=184$, $Z=114(120,126)$. Some of the isotopes have a half-life long enough to study chemical properties.

Actinide nuclei have a prolate deformation, and thus should influence the fusion probability. At the collision on the polar sides the Coulomb barrier is low, and the reaction starts from the distant configuration. Collision on the equatorial side has higher Coulomb barrier, and the reaction starts from the compact shape. We studied the orientation effects on fusion and/or quasifission by measuring the fission fragment mass distributions. With the analysis using fluctuation dissipation model, fusion probability is determined. Validity of the proposed method to determine fusion probability was confirmed by measuring the evaporation residue cross sections for seaborgium ($Z=106$) and hassium ($Z=108$) isotopes.

II. EXPERIMENTAL SETUP

Fission fragment mass distributions in the reactions of ^{30}Si , ^{31}P , $^{34,36}\text{S}$, ^{40}Ar , $^{48}\text{Ca} + ^{238}\text{U}$ were measured using beams supplied by the tandem accelerator of the Japan Atomic Energy Agency (JAEA). The experimental setup and the analysis method were described in [4]. The

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beam intensities were typically from 0.1 to 1.0 p -nA. The ^{238}U target was prepared by electrodeposition of UO_2 on a $90\text{-}\mu\text{g}/\text{cm}^2$ thick nickel backing. Both fission fragments (FFs) were detected in coincidence by position-sensitive multiwire proportional counters (MWPCs) having an active area of $200\text{mm}(\text{H}) \times 120\text{mm}(\text{V})$. The detectors were located on both sides of the target at a distance of 211 mm. The detector center was placed to optimize the efficiency to detect fission fragment in coincidence. The MWPCs covered the emission angle of $\pm 25.0^\circ$ around the detector center.

The time difference, ΔT , between the signals from the cathodes of MWPC1 and MWPC2 was measured. The charges induced in two MWPCs contain information on the energy deposition ΔE_1 and ΔE_2 of particles traversing the detectors and were recorded.

Fission events occurring after complete transfer of the projectile momentum to the composite system (full momentum transfer (FMT) fission) were separated from those fission events following nuclear transfer by recording the folding angle formed by two fission fragments.

III. EXPERIMENTAL RESULTS

The cross-sections for the FMT fissions (σ_{fiss}) in $^{36}\text{S} + ^{238}\text{U}$ are shown in Fig.1 as a function of center-of-mass energy $E_{\text{c.m.}}$. The cross-sections are almost equal to those of the projectiles being captured inside the Coulomb barrier (σ_{cap}). In order to see the influence of nuclear properties on the capture cross-sections, we performed a coupled-channels calculations using the computer code CCDEGEN [5]. We used the same parameters for the nuclear potential as in our previous work for the reactions $^{16}\text{O} + ^{238}\text{U}$ [6]. The dashed curve in Fig.1 is the result without considering any collective properties of target and projectile (one-dimensional barrier penetration model). This model does not reproduce the cross-sections for $E_{\text{c.m.}} < 160$ MeV. The dash-dotted curve represents the calculation taking into account the deformation of ^{238}U with $\beta_2 = 0.275$ and $\beta_4 = 0.05$ [6, 7]. These results reproduce the data well down to $E_{\text{c.m.}} = 146.0$ MeV, showing that the static deformation of ^{238}U is the main reason for the cross-section enhancement at sub-barrier energies. Data at the two lowest energies of 142.0 and 140.0 MeV are reproduced, when couplings to vibrational states are additionally taken into account (solid curve). In this case the 2^+ state at 3.29 MeV in ^{36}S ($\beta_2 = 0.16$ [8]) and the 3^- state at 0.73 MeV in ^{238}U ($\beta_3 = 0.086$ [9]) were considered.

The measured fission fragment mass distributions in the reactions of ^{30}Si , ^{31}P , ^{36}S , ^{40}Ar , $^{48}\text{Ca} + ^{238}\text{U}$ are shown in Fig.2 [10–12]. In each reaction, data at four incident energy points are shown.

In the ^{30}Si , ^{31}P and ^{36}S -induced reactions, we observed a mass-symmetric distribution at the highest incident energy. The mass-asymmetric fission channel appears at the low energies. The variation of the measured distri-

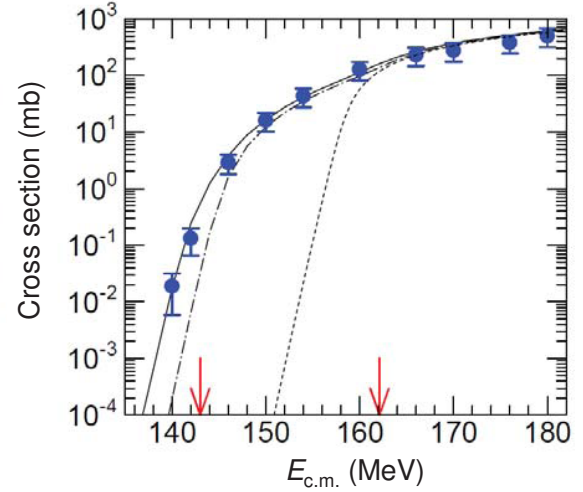


FIG. 1. Cross-sections for the full momentum transfer (FMT) fission of the reaction $^{36}\text{S} + ^{238}\text{U}$. Curves represent the results of coupled-channel calculations (see text). The Coulomb barriers for polar and equatorial collisions are at 143.0 and 162.1 MeV, respectively, as indicated by the arrows.

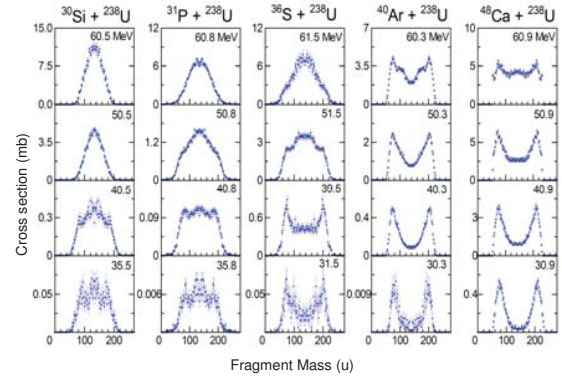


FIG. 2. Fission fragment mass distributions of full momentum transfer fission. The numerical value in each section of the figure show the excitation energy of the compound nucleus. Integration of the cross section all over the mass gives the total fission cross section.

butions with incident energy is interpreted as the effects of nuclear orientation on the reaction. At the lowest incident energy, the reaction is limited to the collision on the polar sides of the nucleus ^{238}U . This configuration leads to quasifission with larger probability than the reaction starting from equatorial collisions. It is evident from Fig.2 that quasifission probability increases with the mass and/or charge of projectile nucleus. In the reactions using ^{40}Ar and ^{48}Ca beams, mass-asymmetric quasifission dominates for all incident energies. However, fraction of the symmetric-fission increases with incident energy, showing the orientation effects.

In order to make a quantitative analysis of the mass dis-

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