Fission probability of ^{239}U at high excitation measured with the ^{238}U(α,^{3}Hef) reaction

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The fission probability of ^{239}U has been measured as a function of excitation energy using the ^{238}U(α,^{3}Hef) reaction with $E_\alpha = 152$ MeV. The ^{3}He spectrum in coincidence with fission exhibits a broad peak near the incident beam velocity. The deduced fission probability is the same as that obtained from the ^{238}U(n,f) reaction. This suggests that the neutron transfers to the target forming a compound nucleus ^{239}U, while the ^{3}He, acting as a spectator, escapes with the incoming beam velocity.

[NUCLEAR REACTIONS ^{238}U(α, ^{3}Hef) measured $\sigma(E)$, fission probability to E_x ~40 MeV, discuss reaction mechanism.]

Recently, considerable interest has been focused on the study of composite projectile induced reactions, especially in an effort to understand the contribution of preequilibrium, projectile fragmentation, incomplete fusion, and fusion processes to the reaction mechanisms.[1-4] Measurements involving particle-particle angular correlations, particle-gamma correlations, and fission-fragment angular correlations have been used to help identify the various reaction mechanisms.[3,4] It has been pointed out that processes of particle transfer (or stripping) into the nuclear continuum (more recently referred to as incomplete fusion) play a significant role in both heavy-ion and light-ion induced reactions.[4] Furthermore, particle-transfer processes are generally associated with the production of a projectilelike fragment.[4] In this paper, we report a measurement of the particle-transfer cross section for the reaction channel ^{238}U(α, ^{3}He) in which ^{3}He particles were detected in coincidence with two fission fragments.

For our studies, the use of the alpha particle rather than a heavier ion as a projectile has the advantage that fewer particle-transfer channels are available. Furthermore, our results can be compared with available data from the ^{238}U(n,f) reaction. Selection of high energy ^{3}He particles in coincidence with fission fragments ensures that the ^{3}He is not produced from the decay of a compound nucleus formed by complete fusion of the projectile and target. By measuring the energy of the outgoing ^{3}He particles in coincidence with fission fragments, the properties of the fission deexcitation can be studied over a large and continuous region of excitation energy.

The experiments were carried out in a 2-m diameter scattering chamber by bombarding self-supporting 800 μg/cm^2 ^{238}U targets with 152 MeV alpha particles from the Indiana University Cyclotron Facility. The spectrum of ^{3}He particles was measured at 11.5° using a counter telescope consisting of 3500 μm thick (ΔE) and 5000 μm thick (E) silicon surface-barrier detectors. Fission fragments were detected in two position-sensitive gas-proportional counters which covered an angular range of −63° to −85° (opposite to the ^{3}He detector) and 92° to 120° (same side as the ^{3}He detector). The fission fragment detectors subtended 1° vertically. The ^{3}He singles spectrum was obtained simultaneously with the spectrum of ^{3}He particles in coincidence with fission fragments. The ^{3}He spectrum covered an energy range from ~95 MeV to the maximum kinematically allowed energy for the (α, ^{3}He) reaction, ~136 MeV. This range of ^{3}He energies observed in our experiment corresponds to an excitation energy range in ^{239}U from 0 to ~40 MeV. The correlation angles between the two fission fragments for ^{239}U recoil momenta corresponding to this range of excitation energies varies only a few degrees (~176° to 180°); thus, both fission fragments are detected in coincidence. The triple coincidence data (α, ^{3}Heff) were corrected for accidental coincidences.

A broad peak near the beam velocity ($\sim \frac{3}{4}E_\alpha$) is observed in the ^{3}He singles spectrum shown in Fig. 1. The spectal shape is similar to that previously reported for ^{3}He singles spectra from 140 and 160 MeV alpha-particle bombardment of ^{209}Bi.[2] Peaks are clearly visible from the (α, ^{3}He) reaction in ^{12}C contamination of the target. However, the contribution to the higher excitation energy spectra from ^{12}C contamination is very small. The fission coincidence spectra will, of course, have no contribution from light contaminants. The shape of the coincidence ^{3}He spectrum (Fig. 2) is similar to that of the singles spectrum; the differ-

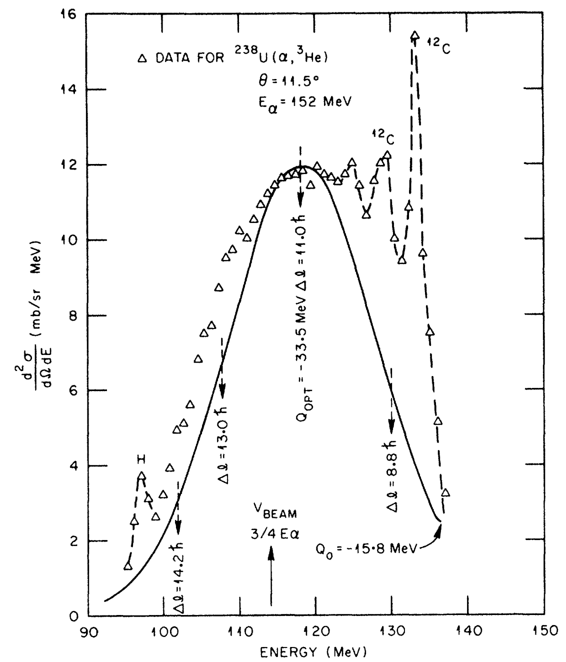

FIG. 1. The ^{3}He singles spectrum at 11.5°. The solid curve was calculated from the Brink model. The optimum Q-value and angular momentum transfers are indicated at selected points at Q_{opt} and Δl . V_{beam} indicates the beam velocity. Q_0 is the g.s. Q value. Sharp peaks indicated as H and ^{12}C arise from the H and ^{12}C contaminants.

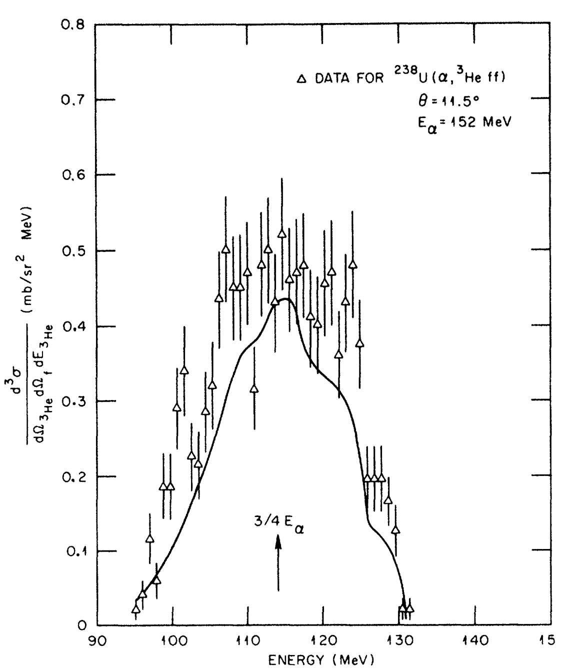

FIG. 2. The ^{3}He spectrum in coincidence with fission-fragments. The solid curve is calculated as described in the text.

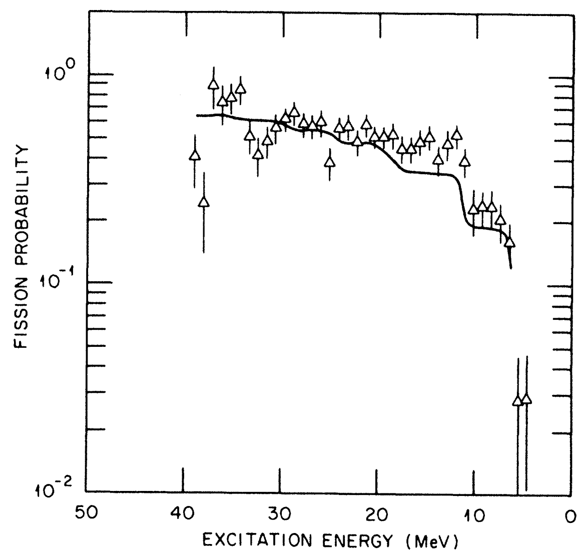

FIG. 3. The fission probability of ^{239}U as a function of excitation energy. △: from the ^{238}U(α, ^{3}Heff) reaction, —: from the ^{238}U(n, f) reaction.

ence at high ^{3}He energies arises because the fission threshold in ^{239}U occurs at an excitation energy of 6.2 MeV. The fission probability, which is the ratio of the coincidence spectrum to the singles spectrum, is shown in Fig. 3. We assume the fission-fragment angular distribution is isotropic at all excitation energies in ^{239}U. The fission probability resulting from the ^{238}U(n,f) reaction (Ref. 5) for excitation energies below 25 MeV is also shown in Fig. 3. Above this energy, the fission probability was calculated using the intranuclear cascade model[6] which includes particle evaporation. The stepped shape of the solid curve is due to multiple chance fission following neutron evaporation. The agreement between the fission probabilities deduced from our (α, ^{3}He) data and the (n,f) reaction is striking. Our experimental results therefore suggest that the dominant mechanism for the production of beam-velocity ^{3}He particles is the transfer of a neutron from the projectile to the target forming a compound nucleus, ^{239}U, which then decays statistically. Other reaction mechanisms such as alpha particle breakup, ^{238}U(α, ^{3}He n)^{238}U*, may contribute,[2,4,7] but only for ^{3}He energies $\lesssim$ 103 MeV. Therefore, these processes only affect the fission probability data (Fig. 3) above an apparent ^{239}U excitation energy of ~33 MeV.

It has been shown[2] that the singles ^{3}He cross section from the (α, ^{3}He) reaction exhibits an ~$A^{1/3}$ dependence, indicating that the reaction is peripheral. Consequently, we compare our data with predictions of two simple direct reaction models.

Figure 1 shows the ^{3}He spectrum (normalized to the data) calculated for the ^{238}U(α, ^{3}He) reaction using the semiclassical transfer reaction model of Brink.[8] This model adequately describes both the optimum Q value for the reaction and the width of the observed spectrum. The optimum angular momentum transfers (Δl) calculated from the Brink model for various ^{3}He energies are also shown on Fig. 1. Similar agreement to the ^{3}He spectral shape is obtained with the Serber stripping model.[9] The results from either the Brink or Serber model, multiplied by the fission probability from the (n,f) reaction, gives the solid curve in Fig. 2. This curve should account for most of the ^{3}He yield in coincidence with fission provided neutron transfer is an adequate description of the reaction mechanism. From the comparison between the calculation and measurement shown on Fig. 2, we conclude that at least 90% of the beam velocity ^{3}He particles are produced by neutron transfer. Assuming that this is also true for the ^{209}Bi(α, ^{3}He) data of Ref. 2 and invoking the $A^{1/3}$ scaling of the cross section, we estimate that the total cross section of the ^{238}U(α, ^{3}Hef) reaction is ~100 mb—or about 4% of the total fission cross section. Thus, this reaction accounts for ~50% of the low momentum transfer fission events observed by Viola *et al.*[3] with 140 MeV α particles on ^{238}U.

In summary, one component of the particle-transfer (incomplete fusion) cross section for the $\alpha + {}^{238}$U reaction has been isolated and the fission probability has been measured over a wide excitation energy range for ^{239}U. The fission probability is in agreement with that obtained from the ^{238}U(n,f) reaction. These measurements indicate that the ^{3}He particle is produced predominately near the beam velocity and behaves as a spectator while the neutron is transferred to the target forming a compound nucleus. The wide range of excitation energies which can be investigated in a single experiment, without appreciable interference from other reaction processes, make the (α, ^{3}He) reaction a useful tool for fission probability measurements.

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