PHYSICAL REVIEW C VOLUME 42, NUMBER 5 NOVEMBER 1990

Fission angular distributions for the systems ^{9}Be+^{232}Th, ^{235}U

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(Received 15 May 1990)

The fission angular distributions for the systems ^{9}Be+^{232}Th, ^{235}U have been measured at $E\sim 50$ and 53 MeV. The measured fission fragment anisotropy values are in good agreement with the expectations of a standard statistical model.

Ramamurthy and Kapoor[1] have proposed the mechanism of preequilibrium fission in order to explain the anomalously large values of fission fragment anisotropies observed in many heavy-ion reactions. It was later suggested[2] by them that a characteristic signature of preequilibrium fission process will be an entrance channel dependence of fission fragment anisotropies for target-projectile combinations across the Businaro-Gallone ridge in the mass-charge asymmetry degree of freedom. To look for such entrance channel effect, measurements have been carried out from ^{3}Be+^{232}Th, ^{235}U systems at Seattle and for ^{10}B, ^{12}B, ^{12}C, ^{16}O+^{232}Th, ^{237}Np systems at Bombay.[3] In the present work, the details of the measurement with a ^{9}Be beam and the results obtained are discussed.

The measurements were carried out at ^{9}Be energies of 50 and 53 MeV using the tandem/booster accelerator facility at Seattle. Enriched ^{235}U (97.5%) and natural ^{232}Th targets of thicknesses 200 and 424 μg/cm^2, respectively, on Ni backing (thicknesses 0.4 and 1 mg/cm^2 respectively) were employed for the measurements. Six silicon surface-barrier detectors ranging in thickness from 20 to 60 μm were positioned suitably to cover the angular range from 80° to 170°. A relative solid-angle calibration of the detectors was obtained using the ^{252}Cf source placed at the target site. In general, the relative solid angles computed from geometry agreed with the ones determined using the Cf source and the two were normalized for the detector placed at $\theta\sim 130°$. A monitor detector was positioned at $\theta\sim 26.5°$ to detect the elastically scattered ^{9}Be. Absolute cross sections were obtained by assuming the measured elastic cross section to be Rutherford (σ_{Ru}) and using the formula

$$W(\theta)=\frac{Y_F\Omega_{\mathrm{el}}\sigma_{\mathrm{Ru}}}{Y_{\mathrm{el}}\Omega_F 2}\ , \qquad (1)$$

where the Y's and Ω's are the yields and solid angles of fission (F) and elastic (el) detectors. The measured fragment angular distributions were transformed to the center-of-mass system assuming symmetric mass division and using Viola systematics[4] for the total fragment kinetic energy. In Fig. 1, the fission fragment angular distributions measured for the ^{9}Be+^{232}Th and ^{235}U systems at $E\sim 50$ and 53 MeV are shown. The experimental values of anisotropies [$A=W(180°)/W(90°)$] deduced by fitting Legendre polynomials to the observed angular distributions are shown in Fig. 2 and the total fission cross sections (σ_{fiss}) obtained by integrating the angular distributions are shown in Fig. 3. It is observed that while the σ_{fiss} values are comparable for the two systems, the A values differed significantly.

The quantity anisotropy A is represented as

$$A=1+\frac{\langle I^2\rangle}{4K_0^2}\ , \qquad (2)$$

where $\langle I^2\rangle$ and K_0^2 have the usual meaning.[5] The spin distributions were calculated in the framework of the models of Esbensen[6] and Wong[7] by adjusting the barrier fluctuation parameter ΔR to fit the measured fusion

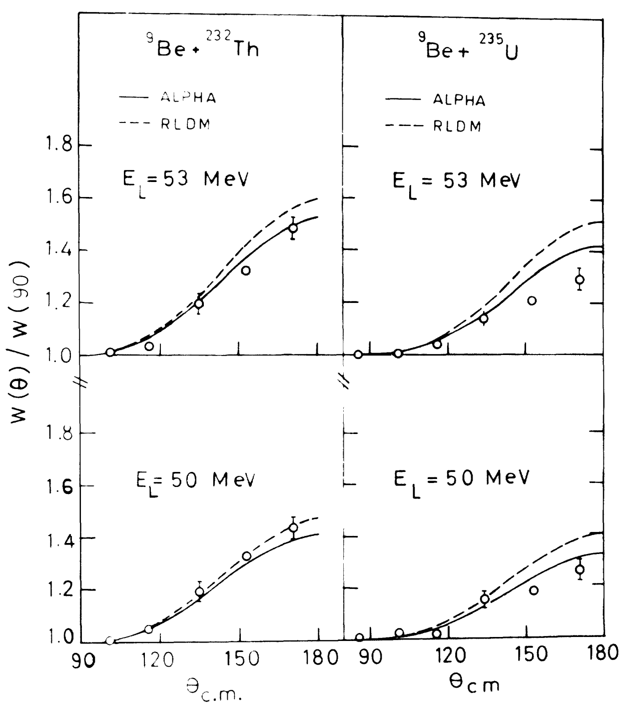

FIG. 1. The fission angular distributions measured for the ^{9}Be+^{232}Th, ^{232}Th, ^{235}U systems at $E\sim 50$ and 53 MeV. The continuous and the dashed lines are the predictions from the standard statistical model using the K_0^2 values deduced from equivalent alpha plus target (experimental) and rotating-liquid-drop model prescriptions as discussed in the text.

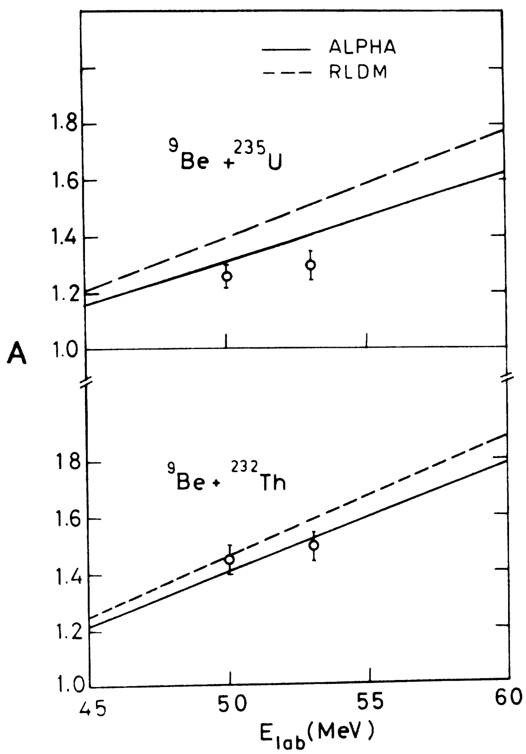

FIG. 2. The experimental and the calculated values of the fission fragment anisotropies for the $^{9}Be+^{232}Th$, ^{235}U systems. The dashed and the continuous lines have same meaning as given in Fig. 1.

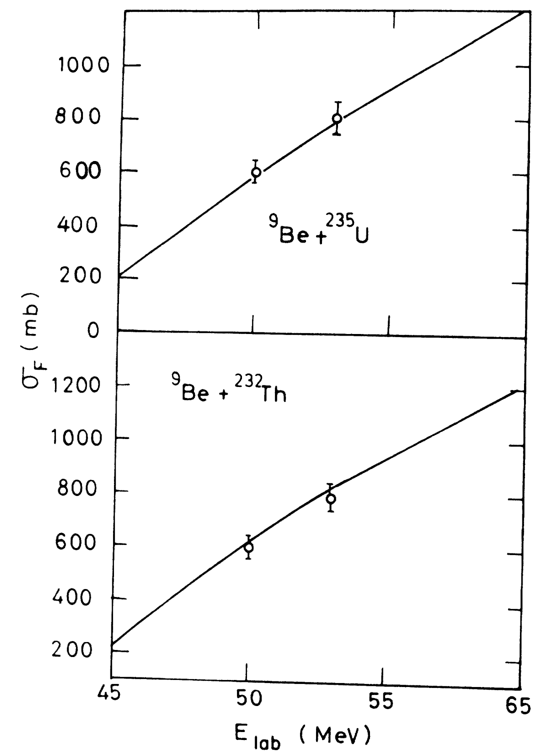

FIG. 3. The fission (fusion) excitation functions for the $^{8}Be+^{232}Th$, ^{235}U systems. The continuous lines are the fits to the data using the prescription of Wong (Ref. 7) and of Esbensen (Ref. 6).

(fission) cross section. We have neglected the target and projectile spin as being small compared to the orbital angular momentum. The relevant parameters are listed in Table I. With these parameters the $\sigma_{\rm fiss}$ data are very well represented by the calculations as can be seen from Fig. 3.

For the calculation of K_0^2 we use the relation

$$K_0^2=\frac{\mathcal{J}_{\rm eff}T}{\hbar^2}\ , \tag{3}$$

where $\mathcal{J}_{\rm eff}$ is the effective moment of inertia and T is the temperature given as $\sqrt{E_x/a}$. We assumed $a=A/8$. Further, using the relation

$$\mathcal{J}_0=\tfrac{2}{5}MR^2 \tag{4}$$

with $R=1.16A^{1/3}$, we have estimated $\mathcal{J}_0$. From the works of Reising *et al.*[8] and Back *et al.*[9] we obtained values for the equivalent alpha plus target systems populating the same compound nuclei as obtained using a ^{9}Be beam. Both the experimental values as well as the ones

TABLE I. Results from the analysis. The top half is $^{9}Be+^{232}Th$. The bottom half is $^{9}Be+^{235}U$.

E (MeV)	$\langle I^2\rangle$	K_0^2 ALPHA	K_0^2 RLDM	$A_{\rm cal}$ ALPHA	$A_{\rm cal}$ RLDM	$A_{\rm expt}$	$\sigma_{\rm fiss}^{\rm calc}$ (mb)	$\sigma_{\rm fiss}^{\rm expt}$ (mb)
		$V_B=41$ MeV $R_B=11.6$ fm $\hbar\omega=4$ MeV						
50	222	174	134	1.32	1.41	1.45	622	598
				1.36[a]	1.47[a]	±0.05		±42
53	292	180	139	1.41	1.53	1.49	815	789
				1.46[a]	1.59[a]	±0.05		±55
		$V_B=41.4$ MeV $R_B=11.6$ fm $\hbar\omega=4$ MeV						
50	214	188	152	1.29	1.35	1.26	586	602
				1.32[a]	1.40[a]	0.05		42
53	286	194	157	1.37	1.46	1.30	795	802
				1.41[a]	1.51[a]	±0.05		±56

[a]Using expression (5).

calculated from rotating-liquid-drop model (RLDM) have been used. Using Eqs. (3) and (4) along with the $\mathcal{J}_0/\mathcal{J}_{\rm eff}$ values, the K_0^2 values have been deduced. Finally, the K_0^2 values for the ^{9}Be+^{232}Th and ^{235}U systems have been obtained by scaling the K_0^2 values deduced above as per $\sqrt{E_x}$.

In Table I, the K_0^2 and $\langle I^2 \rangle$ values obtained for the various systems are tabulated. We have also made detailed angular distribution calculations using the expression

$$W(\theta)=\sum_{I=0}^{\infty}(2I+1)T_I\left[\sum_{K=-I}^{I}\left(\frac{2I+1}{2}\right)\left|d_{0K}(\theta)\right|^2\exp\left(-\frac{K^2}{2K_0^2}\right)\Big/\sum_{K=-I}^{I}\exp\left(-\frac{K^2}{2K_0^2}\right)\right] \quad (5)$$

using K_0^2, T_I (transmission coefficient) values obtained from above-mentioned procedures. The comparison between the data [divided by $W(90°)$] and the calculations are shown in Fig. 1. A similar comparison for the A values as a function E is shown in Fig. 2.

It is observed that the A values calculated using the K_0^2 values scaled from equivalent alpha plus target anisotropies (experimental) are in better agreement with the data than the scaling due to the RLDM prescription. Since the bombarding energies involved are about 6–8 MeV above the barrier values, it may be reasonable to assume that the transfer fission contribution is not significant.

In the present work, we have reported the fission fragment angular distributions for the systems ^{9}Be+^{232}Th and ^{235}U at $E\sim50$ and 53 MeV. This is the first of its kind for ^{9}Be projectile interacting with actinide targets. It is observed that the measured fission fragment anisotropy values are consistent with the standard statistical model calculations and, hence, the present anisotropy values can be considered "normal."

We would like to thank Dr. V. S. Ramamurthy for suggesting to us the relevance of these measurements. One of us (S.K.) would like to thank A. Saxena for his help in making the angular distribution calculations and Dr. S. S. Kapoor for useful discussions. This work was supported by Department of Energy, U.S. and Department of Atomic Energy, India.

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