Fission fragment anisotropies for $^{6,7}Li+^{235,238}U$

A. Parihari[1], S. Santra[2], N. L. Singh[1], K. Mahata[2], P.K. Rath[1], K. Ramachandran[2], B. K. Nayak[2] and S. Kailas[2]

[1]*Department of Physics, The Maharaja Sayajirao University of Baroda, Vadodara - 390002, INDIA*
[2]*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai - 400085, INDIA*
* email: anamikaparihari.87@gmail.com

Introduction

Study of fission fragment (FF) angular distribution using actinide targets has generated a lot of interest because of the observation of anomalously large FF anisotropies in these systems as compared to the statistical saddle point model (SSPM) calculation [1]. Fission reactions involving the above targets but with weakly bound projectiles have additional interest to look for the effect of projectile breakup on fission observables. Freiesleben et al. [2] have observed extra contributions in fission in $^{6,7}Li+^{232}Th,^{238}U$ reactions which are induced by projectile breakup fragments. Large FF anisotropies measured for these systems could not be explained by the SSPM calculations [1]. It was also observed that the total fission cross sections for ^{7}Li induced reactions at sub-barrier energies are smaller than the ones involving ^{6}Li. However, the anisotropies for $^{7}Li+^{232}Th,^{238}U$ reactions were more than those for $^{6}Li+^{232}Th,^{238}U$ reactions which are in turn larger than the SSPM calculations over the entire energy range. To understand the above differences and further investigate the effect of projectile breakup we have measured the FF anisotropies for the reactions involving the same weakly bound projectiles (i.e., $^{6,7}Li$) but with a nearby target nuclide (^{235}U). Since the ground state target spin for ^{235}U is non-zero (7/2), it would also be interesting to see its effect on FF anisotropy particularly at near-barrier energies compared to those for ^{238}U target. Measurements involving ^{238}U target have also been repeated using the same experimental setup in order to avoid any systematic error while comparing the data for $^{235,238}U$ targets. The experimental data for $^{6,7}Li+^{235}U$ reactions have already been reported in last DAE symposium [3]. In the present paper, we report the newly measured experimental data for all four reactions, i.e., $^{6,7}Li+^{235,238}U$ along with the improved calculations for anisotropies including the breakup effect.

Measurement Details

Fission fragment angular distribution measurements were carried out using the 14 UD BARC-TIFR pelletron accelerator at Mumbai. Beam ($^{6,7}Li$) energies between 26 to 44 MeV in the step of 2 MeV have been used. Targets of $^{235,238}U$ of thickness ~1.6 mg/cm^2 were prepared by electro deposition on 4 μ-inch Ni-Cu foil as backing. The FFs were detected using five ΔE-E silicon surface barrier detectors of thickness 12-15 μm and 300 μm respectively. Two Si surface barrier detectors, kept at 30^0 and 40^0 were used as monitor for absolute normalization of fission cross sections. The measured FF angular distributions in center of mass W(θ) were fitted with the standard expression for angular distribution [4] to determine the anisotropies, A= W(180^0)/W(90^0). Measured FF anisotropies (A) for all the reactions are shown in Fig 1. Total fission (fusion) excitation function (σ_{fiss}) was obtained by integrating the measured FF angular distribution for each beam energy.

Results and Discussion

First, we compared the data with the predictions of the statistical saddle point model (SSPM). The value of anisotropy can be easily calculated by the simpler equation, $A=1+\langle l^2\rangle/4K_o^2$, approximated from the expression for fission fragment angular distribution given in [4], where, $\langle l^2\rangle$ is the mean squared angular momentum of the fissioning nucleus and $K_o^2=(I_{eff}/\hbar^2)T$ is the variance of the K distributions. Here, I_{eff} is the effective moment of inertia and T (=√{E*/a} with a=A_{CN}/9 MeV^{-1}) is the saddle point temperature of the compound nucleus. Excitation energy E^* at the saddle point is given by $E^*=E_{c.m} + Q - B_f - E_{rot} - E_n$

where, Q is the Q-value for the formation of the compound nucleus. The spin dependent fission barrier (B_f), ground state rotational energy (E_{rot}), and effective moment of inertia (I_{eff}) are calculated using the Sierk model [5]. E_n is the average energy removed by the evaporated neutrons from the compound nucleus. The values of $<l^2>$ were derived from the fit to σ_{fiss} with coupled-channels calculations.

The predicted values of anisotropy by SSP Model are shown in Fig. 1 as dot-dashed lines which were found to be on an average smaller than the experimental values for all the reactions except ^{6}Li+^{235}U. It was also observed that the angle integrated fission cross sections involving ^{6}Li (having lower breakup threshold) at near and below barrier energies are larger (not shown here) compared to those involving ^{7}Li (with larger breakup threshold) implying a possible contribution from breakup-induced fission. So, a correction in anisotropy calculation due to breakup is necessary. Projectile breakup being a peripheral reaction, it leads to an increased value of mean-square average of "l" for the breakup induced fission events. Since a breakup fragment carrying only a fraction of the beam energy to the compound nucleus, its excitation energy E^* or temperature T is smaller leading to a reduced value of "K_0^2". Thus modified values of both l and K_0^2 will result in an increase in FF anisotropy. Now, the experimental anisotropy is divided into two parts: complete fusion-fission and breakup fusion-fission. For the latter part, a quantitative estimate was made by calculating the individual anisotropies (A_d and A_t) for the reactions involving same target but with d or t (breakup fragments) as projectile by SSP model but with modified values of "K_0^2" and 'l'. Following assumptions were made: (i) breakup induced fissions are dominated by the capture of lighter fragments (d or t), (ii) beam energy for d is 1/3rd of ^{6}Li and for t is 3/7th of ^{7}Li, (iii) fraction of breakup induced fission is 30% and 25% corresponding to ^{6}Li and ^{7}Li induced reactions respectively. These assumptions are based on the systematics on complete fusion suppression and incomplete fusion fractions for several reactions involving weakly bound projectiles available in the literature. Thus, final anisotropies were taken to be the sum of the contributions from complete-fusion fission and breakup-fusion fission, i.e., $A^{corr}=0.7*A_{6Li}+0.3A_d$ and $0.75*A_{7Li}+0.25A_t$ for ^{6}Li and ^{7}Li induced reactions respectively. Results of the above anisotropy calculations are shown as solid lines in Fig. 1. It can be observed that the corrected anisotropies are much closer to the experimental data. Measured anisotropies corresponding to ^{6,7}Li+^{238}U are larger compared to those for ^{6,7}Li+^{235}U. This could be due to the difference in ground state spin of the two targets. A non-zero g.s. spin of either projectile or a target is known to broaden the K_o^2 distribution leading to a decrease in anisotropy.

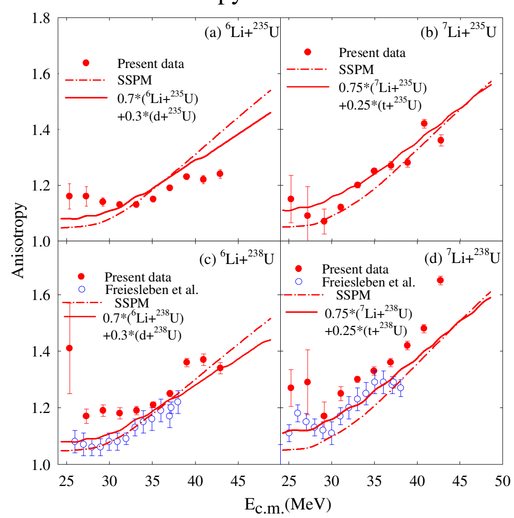

Fig.1. Experimental (filled circles) and calculated fission fragment anisotropies as a function of bombarding energy for ^{6,7}Li + ^{235,238}U systems. Hollow circles represent the data from literature [2]. Solid and dot-dashed lines correspond to SSPM calculations with and without the effect of projectile breakup.

Acknowledgment
One of the authors (A. P.) acknowledges the financial support of UGCDAE-CSR project "GCU/UGCDAE/329/3/872".

References
[1] S. Kailas, Phys. Rep. 284, 381 (1997)
[2] H. Freiesleben, G. T. Rizzo, Z. R. Huizenga, Phys. Rev. C 12, 42 (1975).
[3] A. Parihari et al., Proc. DAE Symp. Nucl. Phys. **56**, 618 (2011)
[4] R. Vandenbosch and J.R. Huizenga, Nuclear Fission (Academic press, New York, 1973).
[5] A. J. Sierk, Phys. Rev. C 33, 2039 (1986).