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Non-compound-nucleus fission events and standard saddle-point statistical model

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The large body of experimental data on the fission fragments anisotropies is analyzed in several heavy-ion-induced fission reaction systems. The entrance channel mass asymmetry parameters of these systems are put on both sides of the Businaro-Gallone mass asymmetry parameters. The role of the mass numbers of the projectile and the target in the prediction of a normal or an anomalous behavior in angular anisotropy as well as the validity of the standard saddle-point statistical model are considered. The average contribution of non-compound-nucleus fission for the systems with an anomalous behavior in anisotropy are also determined.

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I. INTRODUCTION

During almost seven decades of research, an immense body of experimental data on fission processes has been accumulated. In addition, a tremendous effort has been invested in its theoretical understanding. Nevertheless, a full understanding of the fission process has still not been reached. The angular distribution of fission fragments in the heavy-ion-induced fission reaction is an effective probe to study the dynamics of fission reactions. Non-compound-nucleus (NCN) fission is an important area in the field of nuclear fission. In this process, the target and projectile come in contact forming a composite system in which the system reseparates before reaching a compact compound nucleus (CN). Due to the presence of the NCN fission events, fission fragment anisotropies have been observed to be anomalous in comparison to the prediction of the standard saddle-point statistical model (SSPSM), also the widths of the fission fragment mass distributions have been observed to be large in comparison to the CN fission events. In addition, the entrance channel properties, such as the mass asymmetry (α) of the interacting systems with respect to the Businaro-Gallone mass asymmetry parameter ($\alpha_{\rm BG}$), deformation of interacting nuclei, the bombarding energy relative to the fusion barrier, the nuclear orientation of the interacting nuclei such as the collision with the sides of the deformed target nucleus, and the product of $Z_P Z_T$ of the interacting systems (where Z_P and Z_T are the projectile and target atomic numbers, respectively) play an important role in the formation of CN. It was also reported that with deformed targets/projectiles shell effects play a major role in the survival probability of the CN [1,2]. It is well known that the SSPSM as a standard theory of fission fragment angular distributions has been generally used to explain the observed anisotropy data and it is based on the assumption that the fission fragments are emitted along the symmetry axis of the fissioning nucleus and the K component of the total angular momentum I along the symmetry axis is conserved during the descent saddle to scission point [3]. Although the SSPSM as the oldest model has had outstanding success for several induced fission reactions by lighter projectiles, the angular anisotropies for several heavy-ion-induced fusion-fission reactions are significantly higher than those expected from the SSPSM predictions. A majority of the existing models attribute the observation of anomalous behaviors in angular anisotropies of fission fragments to the presence of NCN fission (NCNF) mechanisms such as quasifission (QF), fast fission (FF), and pre-equilibrium fission (PEF), rather than to the breakdown of the SSPSM. It was reported that for the induced reactions by heavy projectiles ($A_P \geqslant 20$) on various targets above the fusion barrier, the measured angular anisotropies were larger than the SSPSM predictions [4,5]; these anomalous behaviors in angular anisotropy were also attributed to the contribution of NCNF(QF) events. Nevertheless, we observe normal behaviors in the measured anisotropies for many induced fission reactions by heavy projectiles ($A_P \geqslant 20$) [6–8]. However, later experimental angular anisotropies were obtained for the reactions induced by light projectiles ($A_P \leqslant 20$) on actinide targets in which the anisotropy could not be explained by SSPSM. For example, in the ^{16}O $+^{238}$U reaction system, the contribution of NCNF was related to the deformed actinide target nucleus [1,9]. While, it is observed anomalous behaviors in the fission fragment anisotropies for the induced fission of ^{238}U target by ^{16}O and ^{19}F projectiles, and also for the induced fission of ^{232}Th target by ^{16}O, ^{19}F and ^{14}N projectiles at energies near coulomb barrier, it is found normal behaviors in measured anisotropies for several reactions induced by light projectiles ($A_P \leqslant 20$) [6–8,10–15]. In the literature, it was reported that for systems with the entrance mass asymmetry $\alpha[\alpha = \frac{(A_T - A_p)}{(A_T + A_p)}]$ greater than the Businaro-Gallone critical mass asymmetry parameter $\alpha_{\rm BG}$ ($\alpha_{\rm BG}$ is parameterized as $\alpha_{\rm BG} = 0$ for $\chi < \chi_{\rm BG}$, and $\alpha_{\rm BG} = 1.12\sqrt{\frac{(\chi - \chi_{\rm BG})}{(\chi - \chi_{\rm BG}) + 0.24}}$ for $\chi > \chi_{\rm BG}$, where χ is the fissility parameter, and $\chi_{\rm BG} = 0.396$ [16]), the measured fragment anisotropies are in agreement with the SSPSM predictions, while in the case $\alpha < \alpha_{\rm BG}$, the experimental fragment anisotropies obviously deviate from the SSPSM calculations [13,17]. However, for the ^{11}B $+^{232}$Th [10] reaction system having $\alpha > \alpha_{\rm BG}$, as well as for ^{19}F $+^{208}$Pb [18], ^{16}O $+^{208}$Pb [19], ^{19}F $+^{209}$Bi [20], and ^{16}O $+^{209}$Bi [21] reaction systems with $\alpha < \alpha_{\rm BG}$, the angular anisotropies show anomalous and normal behaviors, respectively. There are several heavy-ion-induced systems having $\alpha > \alpha_{\rm BG}$ with anomalous behaviors in angular anisotropies,

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TABLE I. Heavy-ion-induced fission systems with unexpected behaviors in angular anisotropies of fission fragments. These behaviors are not expected by the comparison between the entrance channel mass asymmetry (α) and the Businaro-Gallone critical mass asymmetry (α_{BG}).

Fission systems	Comparison between α and α_{BG}	NCNF contribution	References
$^{9}Be + ^{232}Th$	$\alpha(=0.925)>\alpha_{BG}(=0.882)$	Yes	[22]
$^{11}B + ^{243}Am$	$\alpha(=0.913)>\alpha_{BG}(=0.903)$	Yes	[23]
$^{12}C + ^{232}Th$	$\alpha(=0.902)>\alpha_{BG}(=0.890)$	Yes	[10]
$^{12}C + ^{235}U$	$\alpha(=0.903)>\alpha_{BG}(=0.898)$	Yes	[10,24]
$^{12}C + ^{236}U$	$\alpha(=0.903)>\alpha_{BG}(=0.897)$	Yes	[10,24]
$^{12}C + ^{238}U$	$\alpha(=0.904)>\alpha_{BG}(=0.896)$	Yes	[10,24]
$^{16}O + ^{182}W$	$\alpha(=0.838)<\alpha_{BG}(=0.840)$	No	[25]
$^{16}O + ^{186}Os$	$\alpha(=0.842)<\alpha_{BG}(=0.850)$	No	[8]
$^{16}O + ^{188}Os$	$\alpha(=0.843)<\alpha_{BG}(=0.849)$	No	[8]
$^{16}O + ^{194}Pt$	$\alpha(=0.848)<\alpha_{BG}(=0.863)$	No	[26]
$^{16}O + ^{197}Au$	$\alpha(=0.850)<\alpha_{BG}(=0.861)$	No	[27]
$^{18}O + ^{197}Au$	$\alpha(=0.833)<\alpha_{BG}(=0.860)$	No	[28]
$^{19}F + ^{184}W$	$\alpha(=0.813)<\alpha_{BG}(=0.843)$	No	[29]
$^{19}F + ^{188}Os$	$\alpha(=0.816)<\alpha_{BG}(=0.853)$	No	[30]
$^{19}F + ^{192}Os$	$\alpha(=0.820)<\alpha_{BG}(=0.849)$	No	[30]
$^{19}F + ^{194}Pt$	$\alpha(=0.822)<\alpha_{BG}(=0.861)$	No	[31]
$^{19}F + ^{197}Au$	$\alpha(=0.824)<\alpha_{BG}(=0.865)$	No	[32]
$^{19}F + ^{198}Pt$	$\alpha(=0.825)<\alpha_{BG}(=0.858)$	No	[31]
$^{24}Mg + ^{178}Hf$	$\alpha(=0.762)<\alpha_{BG}(=0.850)$	No	[8]
$^{24}Mg + ^{192}Os$	$\alpha(=0.778)<\alpha_{BG}(=0.865)$	No	[33]
$^{24}Mg + ^{197}Au$	$\alpha(=0.783)<\alpha_{BG}(=0.879)$	No	[33]
$^{27}Al + ^{186}W$	$\alpha(=0.764)<\alpha_{BG}(=0.861)$	No	[27]
$^{28}Si + ^{176}Yb$	$\alpha(=0.725)<\alpha_{BG}(=0.849)$	No	[6]
$^{34}S + ^{168}Er$	$\alpha(=0.663)<\alpha_{BG}(=0.850)$	No	[7]

as well as systems having $\alpha < \alpha_{BG}$ with normal behaviors in angular anisotropies as indicated in Table I.

The model of Ramamurthy and Kapoor [34] gives a quantitative estimate of the effect of NCNF on fission fragment angular distribution. According to this model, the probability of NCNF events (P_{NCNF}) is given by an approximate expression as follows

$$P_{NCNF}(I) = \exp[-0.5B_f(I, K=0)/T_{sad}], \tag{1}$$

where B_f and T_{sad} are the fission barrier height and the temperature at the saddle point, respectively. Recently, the investigations of the fission fragment mass angle correlations and mass ratio distributions as well as the analysis of the variance of the mass distributions as a function of temperature and angular momentum was used for the presence of QF in heavy-ion-induced fission reactions [27]. A sudden change in the standard deviation (a sudden increase in the standard deviation as energy decreases to below-barrier energies) of the fission fragments mass distribution as a function of $E_{c.m.}/V_b$ (where $E_{c.m.}$ and V_b are the projectile energy in the center of mass and the Coulomb barrier, respectively), the observation of an anomalous behavior in fission fragment anisotropies, the measurement of an evaporation residue cross section, and the measurement of prescission neutron multiplicity are known as the different probes for the presence of PEF and QF for several heavy-ion-induced fission systems [35]. It must be pointed out that the product of $Z_P Z_T$ (where Z_P and Z_T are the projectile and target atomic numbers, respectively) of the interacting systems plays an important role in the formation of the CN. Although in the past it was predicted that QF occurs when $Z_P Z_T \geqslant 1600$ [36], recent results show that the onset of QF starts at a $Z_P Z_T$ value equal to nearly 1000 and plays a dominant role at higher values of $Z_P Z_T$ [8]. With this motivation, the purpose of the present paper is to obtain a relation in terms of projectile and target mass numbers by analyzing the large body of experimental data on fission anisotropies for the determination of the validity of SSPSM.

II. METHOD OF CALCULATIONS

A. Standard saddle-point statistical model and the calculation of SSPSM predictions

According to statistical theory, fission fragments angular distribution $[W(\theta)]$ for a spin zero projectile-target combination is given by the following expression [37]

$$W(\theta) \propto \sum_{I=0}^{\infty} \frac{(2I+1)^2 T_I \exp\left[-\left(I+\frac{1}{2}\right)^2 \sin^2\theta/4K_\circ^2\right] J_0\left[i\left(I+\frac{1}{2}\right)^2 \sin^2\theta/4K_\circ^2\right]}{\left(2K_\circ^2\right)^{1/2} \mathrm{erf}\left[\left(I+\frac{1}{2}\right)/\left(2K_\circ^2\right)^{1/2}\right]}, \tag{2}$$

where T_I, K_0^2, and J_0 are the transmission coefficient for fission, the variance of the K distribution [K is the component of the angular momentum vector (I) on the symmetry axis of the fissioning nucleus], and the zeroth-order Bessel function, respectively. The variance of the K distribution is calculated by the following relation

$$K_\circ^2 = \frac{\Im_{eff} T_{sad}}{\hbar^2}, \tag{3}$$

$\Im_{eff}$ and T_{sad} are the effective moment of inertia and the nuclear temperature of the compound nucleus at the saddle point, respectively. The nuclear temperature of the compound nucleus at the saddle point is given by

$$T_{sad} = \sqrt{\frac{E_{ex}}{a}} = \sqrt{\frac{E_{c.m.} + Q - B_f - E_R - \nu E_n}{a}}. \tag{4}$$

In this equation, E_{ex} denotes the excitation energy of the compound nucleus at the saddle point, while $E_{c.m.}$, Q, B_f, E_R, ν, and E_n represent the center-of-mass energy of the projectile, the Q value, fission barrier height, rotational energy of the compound nucleus, the number of prefission neutrons, and the excitation energy lost due to evaporation of one neutron from the compound nucleus prior to the system reaching to the saddle point. The quantity a stands for the level density parameter at the saddle point. The fission fragment angular distributions are characterized by anisotropy (A), defined as the ratio of the yield at 180° or 0° to that at 90° ($A = \frac{W(0^\circ \text{ or } 180^\circ)}{W(90^\circ)}$). The fission anisotropy in the SSPSM (A_{SSPSM}) is given by an approximate formula [37]

$$A_{\text{SSPSM}} \approx 1 + \frac{< I^2 >}{4K_\circ^2}. \tag{5}$$

In this work, a is taken as $\frac{A_{\text{C.N.}}}{8}$ (by accounting for $\frac{A_{\text{C.N.}}}{10}$ instead of $\frac{A_{\text{C.N.}}}{8}$ in the calculations, the difference will be less than 10%); $\Im_{\text{eff}}$, B_f, and E_R are accounted by the use of a rotating finite range model (RFRM) [38], while $< I^2 >$ quantities are taken from the literature [4,12,39–42]. We used the values of the literature for ν [12,42–46] and E_n is taken as 10 MeV [20,47]. In the present work, the prefission neutrons are taken to be emitted before the saddle point since it is not straightforward to separate experimentally the contribution of neutrons emitted before the saddle point and the ones emitted after the saddle point but before the scission point.

B. Calculation of the average contribution of NCNF anisotropies

In recent years, heavy-ion-induced fission fragments angular distribution measurements performed at below-to-above barrier energies have generated much interest due to the failure of the predictions of the SSPSM for heavy-ion-induced fission of actinide targets [13,48,49]. The effects of entrance channel parameters such as mass asymmetry, target deformation, and target or projectile spins on fission fragment anisotropies were identified in the past from a systematic study of fission fragments angular distributions at energies around the Coulomb barrier energies in actinide targets [13]. Nonequilibrium fission(PEF, QF, and FF) was thought to be a probable cause of this anomaly. Almost 25 years ago, Ramamurthy and Kapoor [34] proposed the pre-equilibrium fission (PEF) model to explain the anomalous anisotropies in several heavy-ion-induced fission reactions at above-barrier energies. The main difference between CN fission and PEF is that in the latter case the K degree of freedom is not equilibrated, but other degrees such as energy and mass asymmetry are fully equilibrated. Therefore the assumption of symmetric mass division is justified in the case of PEF. The K distributions of PEF will be the product of the entrance channel K distribution and the saddle point K distribution [24,50], and the narrower of the above two K distributions governs the fragment anisotropy. This explains the observed larger anisotropies whenever the input K distribution is not fully equilibrated. According to this model, the final K distribution for fissioning nuclei is given by $P_f(K) = P_{\text{initial}}(K)P_{\text{saddle}}(K)$, where $P_{\text{initial}}(K)$ is the K distribution for the initial dinuclear complex and $P_{\text{saddle}}(K)$ is the Gaussian K distribution at the saddle point. On the whole, the final K distribution is governed by the initial narrow K distribution populated in the formation phase. Following the work of the authors of Refs. [24,50], the probability of a fissioning nucleus having the quantum numbers I and K, when populated from an entrance channel K-state distribution with peaks at $\widetilde{K}$ is given by

$$P(J, K, \widetilde{K}) = \exp\left[-\frac{(K-\widetilde{K})^2}{2\sigma_K^2}\right] \times \exp\left[-\frac{(K\hbar)^2}{2\Im_{\text{eff}}T}\right]. \tag{6}$$

$P(J, K, \widetilde{K})$ is obtained by taking the initial K-state distribution for each I value convoluted by a Gaussian with standard deviation σ_K and multiplied by the SSPSM K-state distribution at fission saddle point.

It has been observed that at subbarrier energies all the systems with actinide targets show anomalous anisotropies of varying extent with respect to the SSPSM. To explain such anomalous behaviors in angular anisotropies at subbarrier energies, a few models such as the dependent QF model [1,9], pre-equilibrium model, a model considering the incorporation of target and projectile spins [24,50,51], and the entrance channel dependent K-state model (ECD-K) [50] have been well recognized. It is obvious that the prediction of SSPSM shows the anisotropy of compound nucleus fission (CNF) events, and the experimental values of anisotropies are due to CNF and NCNF events for the systems having anomalous behaviors in angular anisotropies. The average contribution of NCNF anisotropies over the energy range of the projectile (A_{NCN}) for these systems is given by

$$A_{\text{NCN}} = \frac{A_{\text{exp}} - A_{\text{SSPSM}}}{A_{\text{exp}}}. \tag{7}$$

In this equation, A_{SSPSM} is the average contribution of SSPSM prediction over the energy range of the projectile, and A_{exp} stands the average experimental value of anisotropy over the same energy range.

III. RESULTS AND DISCUSSION

The experimental fission fragment angular anisotropies (A) along with the SSPSM predictions for the induced fission of ^{208}Pb target by different projectiles (^{24}Mg, ^{28}Si, and ^{32}S) are shown in Fig. 1. A calculation of the average of NCNF contributions for these three systems over the $1.05 \leqslant \frac{E_{\text{c.m.}}}{V_b} \leqslant 1.35$ energy range show that the NCNF contributions will increase as the mass number of the projectile increases.

We also considered the induced fission of ^{238}U target by ^{16}O, ^{19}F, ^{27}Al projectiles, as well as the induced fission ^{232}Th by ^{16}O, ^{19}F, and ^{32}S projectiles. The average contributions of NCNF for the induced fission of ^{208}Pb, ^{238}U, and ^{232}Th targets by different projectiles are shown in Fig. 2. These average contributions for the induced fission of ^{238}U and ^{232}Th targets by different projectiles are calculated over the $1.0 \leqslant \frac{E_{\text{c.m.}}}{V_b} \leqslant 1.2$ and $0.95 \leqslant \frac{E_{\text{c.m.}}}{V_b} \leqslant 1.15$ energy ranges, respectively. In this figure, the thick solid line shows the contributions of NCNF for the induced fission of the ^{208}Pb target by different projectiles. The points on this thick solid line are the average contributions of NCNF for the ^{24}Mg, ^{28}Si, and ^{32}S $+^{208}$Pb reaction systems. It can be observed that in induced fission of the ^{208}Pb nucleus, the contributions of NCNF for projectiles whose mass number is 20 or less is zero, also there is the average contribution of NCNF for induced fission of this target by projectiles with

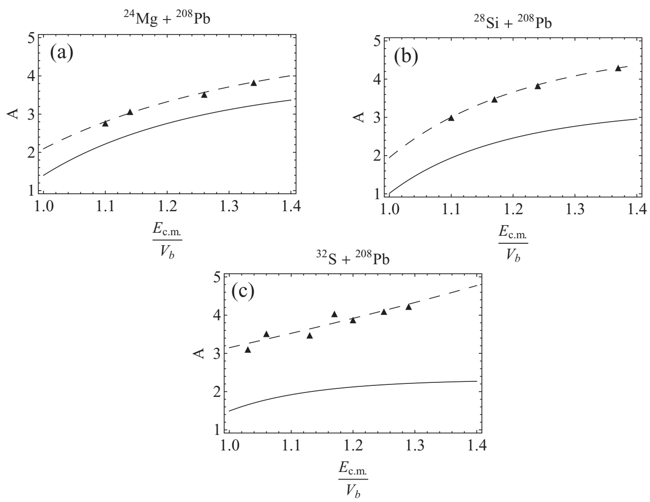

FIG. 1. Experimental data of anisotropy (A) for the fission of the ^{208}Pb target induced by several projectiles. (a) Solid and dashed curves are the SSPSM prediction and experimental value of anisotropy for the fission of the ^{24}Mg +^{208}Pb reaction system. (b) Solid and dashed curves are the SSPSM prediction and experimental value of anisotropy for the fission of the ^{28}Si +^{208}Pb reaction system. (c) Solid and dashed curves are the SSPSM prediction and experimental value of anisotropy for the fission of the ^{32}S +^{208}Pb reaction system [4].

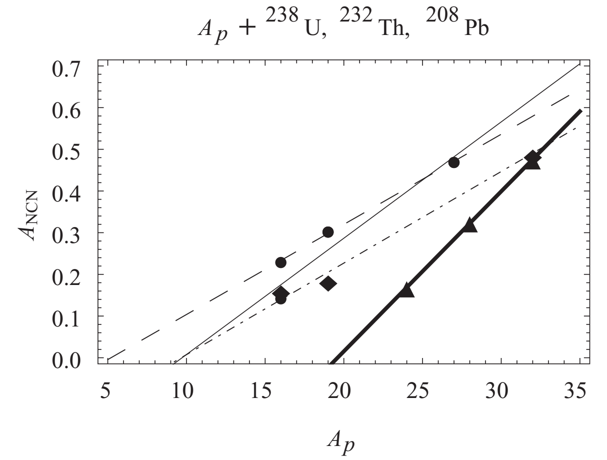

FIG. 2. The average contributions of NCNF (A_{NCN}) versus the mass number of projectile. Thick solid line for ^{208}Pb, thin solid and dashed lines for ^{238}U nucleus by using Back data and by using Nasirov data, respectively, and dashed-dotted line for ^{232}Th target.

the mass number being more than 20. This result is found to be in good agreement with experiments [4]. In this figure, the thin solid, and dashed lines show the average contributions of NCNF for the induced fission of the ^{238}U target by different projectiles. The discrepancy on these two lines is because of the different values of $< I^2 >$ for the induced fission of ^{238}U by the ^{16}O projectile that was taken from different references (Back *et al.*, [4] and Nasirov *et al.* [42]).

The dashed-dotted line in the Fig. 2 shows the average contributions of NCNF for induced fission of the ^{232}Th target by different projectiles over the $0.95 \leqslant \frac{E_{c.m.}}{V_b} \leqslant 1.15$ energy range. It is interesting to note that whenever the target is heavier one can infer the onset of NCNF events occurs with lighter projectiles and vise versa. By considering several heavy-ion-induced fission systems with anomalous behaviors in angular anisotropies, such as ^{24}Mg,^{28}Si, and ^{32}S +^{208}Pb in comparison with ^{16}O, ^{19}F, and ^{27}Al +^{238}U systems, it can be observed that the contributions of NCNF in induced fission of heavier targets are more than the contributions of NCNF in induced fission of lighter target by the same projectile. While the calculated value of the average contributions of NCNF for the ^{32}S +^{197}Au system over the $1.1 \leqslant \frac{E_{c.m.}}{V_b} \leqslant 1.2$ energy range is approximately 44%, this contribution for the ^{32}S +^{208}Pb system over the same energy range is obtained as 50%. The predicted value of average contributions of NCNF for the ^{40}Ar +^{208}Pb system over the $1.05 \leqslant \frac{E_{c.m.}}{V_b} \leqslant 1.3$ energy range from Fig. 2 is approximately 87% which is in good agreement with the work of Keller *et al.* [52]. Itkis *et al.* measured the mass and energy distributions of the ^{56}Fe +^{208}Pb reaction system. They also reported that for this reaction, the QF process dominates at all measured energy [53]. This result is predicted very well in Fig. 2. To make a comparison between the average contributions of NCNF in induced fission of different targets by the same projectile, we calculated these contributions for the induced fission of ^{184}W, ^{197}Au, and ^{208}Pb targets by the ^{32}S projectile, as well as those of the induced fission of ^{232}Th, ^{238}U, and ^{248}Cm targets by ^{16}O projectile over the same energy range. These calculated contributions are shown in Fig. 3. It can be seen from this figure that the average contributions of NCNF for induced fission of different targets by the same projectile begin from a given target mass number. These contributions also show a linear behavior in terms of the mass numbers of targets for a given projectile.

Finally, as indicated in Fig. 4, for the heavy-ion-induced fission reactions systems in which the mass numbers of target and projectile (A_T and A_P, respectively) located below the curve shown in this figure, fission fragment angular anisotropies exhibit normal behaviors. In addition, the predictions of SSPSM are in agreement with the experimental angular anisotropies data. However, for the reactions in which

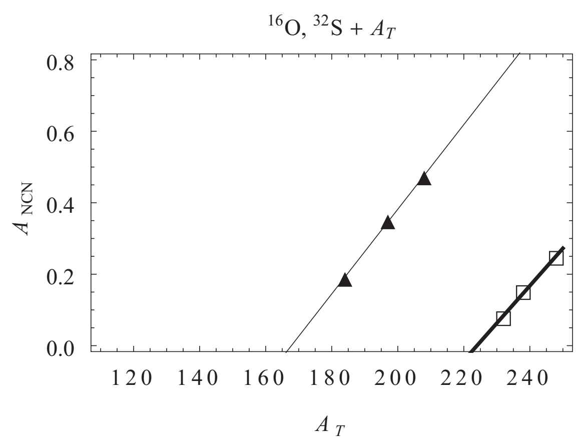

FIG. 3. The average contributions of NCNF (A_{NCN}) for induced fission of different targets by the same projectiles. Thick solid and thin solid lines shows A_{NCN} for induced fission of different targets by ^{16}O and ^{32}S projectiles, respectively.

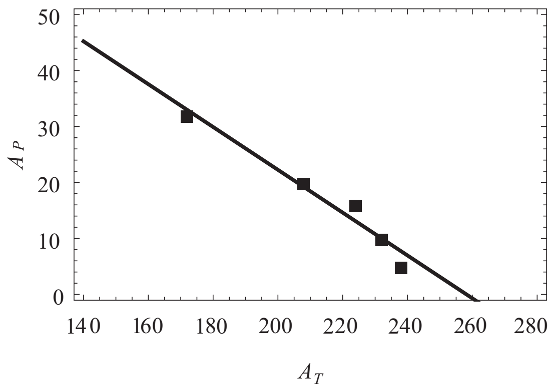

FIG. 4. The border diagram between compound nucleus fissions with compound and noncompound fissions.

A_T and A_P lie above this curve, there exists an admixture of CNF and NCNF events so that the measured fission fragment anisotropies are anomalously large compared to the peredictions based on the SSPSM. As a result this model is not valid.

It is interesting to note that Berriman *et al*. [54] reported a contribution of NCNF for a very asymmetric reaction $^{19}F +$ ^{197}Au system by measuring of the width of the fission fragments mass distribution. However, a recent measurement of fission fragments angular distributions for the same reaction showed no evidence of NCNF [28,32] as can be also seen from Fig. 4. In another work, evidence of NCNF was found in the $^{34}S +$ ^{168}Er reaction system by considering the fission fragment mass distribution, but no evidence for NCNF was observed in the investigation of fission fragment angular distributions [7,8].

Figure 4 shows that the contribution of NCNF is not significant for the induced fission of the ^{168}Er target by the projectiles with $A_P \leqslant 35$. Our results are in agreement with the experimental observations that have been obtained up to now [1,6–8,10,12, 18–21,23,24,27,28,32,35].

IV. SUMMARY AND CONCLUSION

The average contributions of NCNF were calculated for several heavy-ion-induced fission reaction systems having anomalous behaviors in fission fragments angular anisotropies by comparison between the experimental data of fission fragment angular distributions and the predictions of SSPSM. Although, it was reported that for the systems with $\alpha > \alpha_{BG}$, the measured fission fragments anisotropies are in general agreement with the expectation of the SSPSM, as well as for the systems with $\alpha < \alpha_{BG}$, the experimental fragment anisotropies are considerably greater than the predictions of the SSPSM at subbarrier and near-barrier energies. However, there are the reaction systems on different sides of Businaro-Gallone critical mass asymmetry with unexpected behaviors in fission fragments angular anisotropies as indicated in Table I. Our calculated NCNF contributions for the reaction systems with anomalous behaviors in angular anisotropies show that these contributions increase with increasing the mass number of projectiles for a given target. This contribution also exhibits a linear behavior as a function of the mass number of targets for a given projectile. Finally, the validity of SSPSM in the prediction of angular anisotropies for the reaction systems with normal behaviors in fission fragment angular anisotropies is also determined.

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