FOLD DISTRIBUTION ANALYSIS AS A TOOL FOR THE STUDY OF REACTION MECHANISMS AND ENTRY STATE POPULATION DISTRIBUTIONS AT HIGHEST SPINS*

A.A. Pasternak[a,b], R.M. Lieder[b], E.O. Lieder[a,b] and W. Gast[b]

[a]A.F. Ioffe PTI, RU-194021 St. Petersburg, Russia
[b]IKP, Forschungszentrum Jülich, D-52425 Jülich, Germany

(Received November 11, 2004)

Fold distributions for the ^{114}Cd (^{36}S, $\alpha ypxn$) ($E = 182$ MeV), ^{100}Mo (^{48}Ti, $\alpha ypxn$) ($E = 215$ MeV) and ^{97}Mo (^{51}V, $\alpha ypxn$) ($E = 238$ MeV) reactions have been investigated. Evidence for the existence of an incomplete fusion reaction mechanism for the αxn channels has been obtained. The sensitivity of the fold distributions to nuclear deformations at highest spins has been demonstrated.

PACS numbers: 25.70.–z

In Ref. [1] the fold distribution analysis for $^{142-146}$Gd has been applied to the evaluation of the competition between stretched M1 and E2 bands and statistical γ-transitions in the continuum as well as to the evaluation of the spin dependence of the fission barrier $B_{\mathrm{fission}}(L)$ using the ^{114}Cd(^{36}S, xn)$^{144-146}$Gd ($E = 182$ MeV), ^{100}Mo(^{48}Ti, xn)$^{143-145}$Gd ($E = 215$ MeV) and ^{97}Mo(^{51}V, pxn)$^{142-144}$Gd ($E = 238$ MeV) reactions, measured with the γ-spectrometer GASP at LNL [2–4]. In the present work these investigations have been extended to the Eu and Sm nuclei, which are populated in $\alpha ypxn$ and $ypxn$ reaction channels. Fold spectra, measured with the inner BGO ball of GASP, have been obtained for the final nuclei by gating on discrete γ-lines representing transitions above isomers.

We consider in this work a compound nuclear reaction mechanism. The entry state population distributions have been simulated with the Monte Carlo code COMPA using a statistical theory [5]. Our previous investigations [1] have shown that for the regarded compound nuclear reactions the

* Presented at the XXXIX Zakopane School of Physics — International Symposium "Atomic Nuclei at Extreme Values of Temperature, Spin and Isospin", Zakopane, Poland, August 31–September 5, 2004.

high-spin limit of the population distribution is defined by the spin dependence of the fission barrier $B_{\rm fission}(L)$, which are shifted by $\Delta L \approx 4 \pm 1\ \hbar$ compared to the model of Vandenbosch and Huizenga [6]. In the present work we have used the same values of $B_{\rm fission}(L)$. In the Monte Carlo simulation calculations of the deexcitation from the entry states to the final levels statistical E1, M1 and E2 transitions, stretched E2 bands with damping effect and stretched M1 bands with shears effect have been taken into account. The relative density of stretched M1 bands is described by the parameter $S_{\rm mr}$, being the fraction of stretched M1 cascades. By our fold distribution analysis we found [1] that $S_{\rm mr}$ decreases with neutron number in the Gd isotopes. In the present work we have extended this systematics by adding the Eu and Sm isotopes and as can be seen in Fig. 1(b), where $S_{\rm mr}$ is plotted *vs.* $M = (82 - N) + (64 - Z)$, that the new points are in good agreement with the previous ones. Generally, our fold-distribution study shows, that the $ypxn$ and $\alpha ypxn$ reaction channels are connected with compound nuclear formation. Our COMPA calculations indicate that the protons are emitted initially and the α-particles last. The available energy is shared by the emitted particles as observed in Ref. [7].

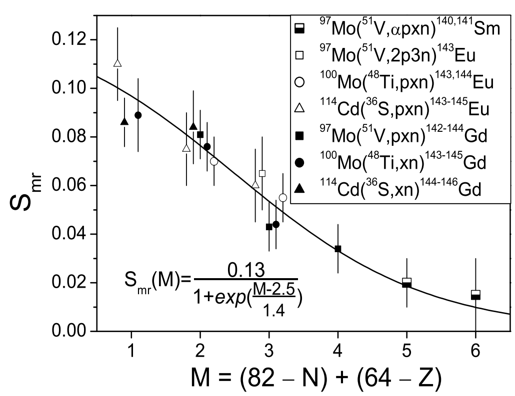

Fig. 1. Fraction of M1 bands $S_{\rm mr}$ *vs.* valence nucleon number M.

In the present work we have obtained evidence that in the case of αxn channels a significant contribution from an incomplete fusion mechanism (ICF) exists: *(i)* the experimental cross sections for these channels exceed significantly (5 to 10 times) the values, calculated assuming a statistical compound nuclear mechanism, *(ii)* the corresponding fold distributions turned out to be shifted in comparison to the expected values. It is illustrated in Figs. 2(a),(b) that this shift is a result of the formation of different compound nuclei by complete (^{36}S + ^{114}Cd $\rightarrow$ ^{150}Gd) and incomplete (^{36}S $\rightarrow$ ^{32}Si + α; ^{32}Si + ^{114}Cd $\rightarrow$ ^{146}Sm) fusion reactions assuming that fission is responsible for the limitation of the input angular momentum. This effect

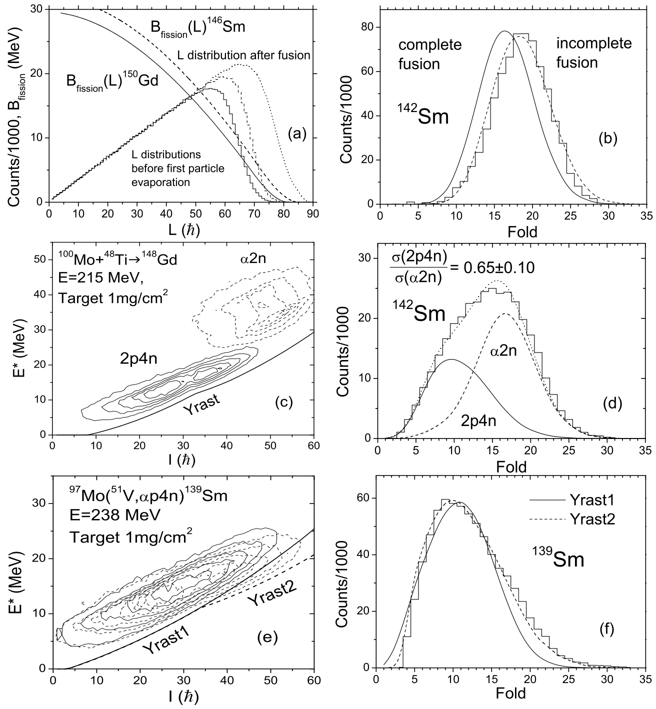

Fig. 2. (a),(b) Dependence of the ^{142}Sm fold distribution on the shift of the fission barrier due to formation of different compound nuclei in complete (^{150}Gd) and incomplete (^{146}Sm) fusion. (c),(d) Superposition of fold distributions for ^{142}Sm due to the $\alpha 2n$ and $2p4n$ channels, respectively, of the ^{100}Mo + ^{48}Ti reaction. (e),(f) Dependence of the ^{139}Sm fold distribution on the location of the yrast line at $I > 35\hbar$. The histograms in the portions (b),(d),(f) represent experimental and the lines calculated fold distributions.

can be used to increase selectively the population of very high spin states. It cannot be excluded that some anomalies in α-particle spectra and cross sections of αxn channels, observed in the population of superdeformed bands of ^{150}Tb [8] and ^{151,152}Dy [9], can be explained by the contribution of an ICF mechanism, keeping in mind that in the mass region $A \approx 150$ α-particle spectra from projectile breakup and compound nuclear evaporation overlap each other. For $A \approx 70$ to 90 at $E \approx 5$ MeV/A evaporation α-spectra due to a lower Coulomb barrier are shifted in comparison to the breakup component and a large contribution due to the ICF mechanism becomes obvious [10]. The cross section of ICF as compared to that of complete fusion can reach 10 to 20% [11], but can be much larger for α-escaping channels so that the large difference between experimental and statistical model calculation values may be explained.

If the same nucleus is populated in both the $ypxn$ and $\alpha(y-2)p(x-2)n$ channels the corresponding spin and multiplicity distributions differ from each other strongly enough that the experimental fold spectra analysis can be applied for the relative channel cross section evaluation. The Figs. 2(c),(d) illustrate the superposition of the fold distributions for ^{142}Sm corresponding to the $\alpha 2n$ and $2p4n$ channels, respectively, of the ^{100}Mo + ^{48}Ti reaction at a beam energy of 215 MeV.

In Figs. 2(e),(f) the influence of the yrast line behavior at highest spins on the fold distribution of ^{139}Sm is demonstrated. For $I > 35\ \hbar$ two different yrast lines are considered. Yrast1 results from the extrapolation of known experimental levels and Yrast2 results if a large deformation is assumed at high spins. In the present experiment due to insufficient statistics the fold distribution may be disturbed by contributions from other reaction channels and Figs. 2(e),(f) may only be considered as evidence that super- and hyperdeformation phenomena should reveal itself in fold distributions.

Generally, the analysis of experimental fold spectra is a powerful instrument for the evaluation of reaction mechanisms and properties of nuclei at very high spins.

The authors would like to thank J.-N. Scheurer and T.L. Khoo for fruitful discussions. This work has been supported by the Deutsche Forschungsgemeinschaft (DFG) by the grant 436 RUS 17/102/03.

REFERENCES

[1] A.A. Pasternak *et al.*, LNL Ann. Rep. 2001, 2002, 2003; Web. Ed. `www.lnl.infn.it`; to be submitted in *Eur. Phys. J.* **A**.

[2] T. Rząca-Urban *et al.*, *Phys. Lett.* **B356**, 456 (1995).

[3] S. Lunardi *et al.*, *Nucl. Phys.* **A618**, 238 (1997).

[4] R.M. Lieder *et al.*, *Nucl. Phys.* **A671**, 52 (2000).

[5] R.M. Lieder *et al.*, *Eur. Phys. J.* **A21**, 37 (2004).

[6] R. Vandenbosch, J.R. Huizenga, in Nuclear Fission, 1973; Program BARRIER of W. Westmeier and A.J. Sierk, LANL T-9 (1984).

[7] F. Bourgine *et al.*, *Phys. Rev.* **C56**, 3180 (1997).

[8] G. Viesti *et al.*, *Phys. Lett.* **B382**, 24 (1996).

[9] M. Aiche *et al.*, *Eur. Phys. J.* **A6**, 121 (1999).

[10] M.F. Kudoyarov *et al.*, *J. Techn. Phys. (Russia)* **68**, 136 (1998); *Heavy Ion Physics*, World Scientific, Singapore 1997, p. 742.

[11] S. Mukherjee *et al.*, *Eur. Phys. J.* **A12**, 199 (2001).