Observation of a Double-humped $\gamma$-Ray Fold Distribution in $^{142}$Eu

R.M. Lieder$^{1,2}$, A.A. Pasternak$^{2,3}$, E.O. Lieder$^1$, W. Gast$^2$, G. de Angelis$^4$, D. Bazzacco$^5$

1 iThemba LABS, Somerset West 7129, South Africa, 2 Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany, 3 A.F. Ioffe Physical Technical Institute, RU-194021 St. Petersburg, Russia, 4 INFN Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy, 5 Dipartimento di Fisica and INFN Padova, I-35131 Padova, Italy

INTRODUCTION

In heavy-ion induced reactions high excitation energies and large angular momenta are transferred to the produced nuclei. The highly-excited nuclei deexcite by long cascades of $\gamma$-ray transitions to the ground state. The number of $\gamma$-rays in each cascade is referred to as $\gamma$-ray multiplicity $M_{\gamma}$. The multiplicity distribution can be measured with $\gamma$-detector arrays equipped with an inner scintillator ball. The number of responding detectors to a $\gamma$-ray cascade of multiplicity $M_{\gamma}$ is called fold $K$. A study of fold distributions allows to obtain information on the reaction mechanism.

EXPERIMENTAL RESULTS

Fold distributions for the population of specific final nuclei around $^{142}$Eu have been derived from high-spin $\gamma$-spectroscopy data obtained with the $\gamma$-detector array GASP of the Laboratori Nazionali di Legnaro, Italy. In this investigation a $^{97}$Mo target has been bombarded with 238 MeV $^{51}$V projectiles. The target consisted of two $^{97}$Mo foils (enrichment 94.2 $\%$) with a total thickness of $\approx$ 1.0 mg/cm$^2$. The GASP array, consisting of 40 bismuth-germanate (BGO) suppressed Ge detectors and a 80 element BGO ball, was equipped with the charged-particle detector array ISIS [1].

Fold distributions, measured in the $^{97}$Mo($^{51}$V,$\alpha\gamma$p$\alpha\gamma$n) reaction with the inner BGO ball of GASP, have been obtained for the final nuclei $^{142-144}$Gd, $^{140-144}$Eu and $^{140,141}$Sm by gating on discrete single $\gamma$-lines in fold $= E_\gamma$ matrices. In the analysis p- and $\alpha$-gated matrices have been used, utilizing the charged particle information obtained with the ISIS array. Here, the results for Eu nuclei will be reported as populated in $\alpha$xn and 2pxn reaction channels [2].

Fold distributions for the 2pxn and $\alpha$xn reaction channels leading to $^{141-144}$Eu are shown in fig. 1. The centroids of the 2pxn fold distributions, shown in the left portion of fig. 1, are gradually shifting to lower folds with an increasing number of emitted neutrons as expected for complete-fusion reactions. However, a completely different picture is found for the $\alpha$xn channels leading to the nuclei $^{140-143}$Eu, as can be seen in the right portion of fig. 1. The centroids of the fold distributions change irregularly with the number of emitted neutrons ($\alpha$4n: $< F > = 11$; $\alpha$3n: $< F > = 16$; $\alpha$n: $< F > = 15$) and the fold distribution of the $\alpha$2n channel leading to $^{142}$Eu shows a double-humped structure with maxima at $< F > = 11$ and 17. Such a fold distribution has to our knowledge not been reported so far.

FIG. 1. Experimental fold distributions for $^{140-144}$Eu obtained for the $\alpha$x$n$ (right portion) and 2px$n$ (left portion) channels in the $^{97}$Mo + $^{51}$V reaction at 238 MeV are shown as histograms. Monte-Carlo simulations of the fold distributions calculated assuming a complete fusion reaction mechanism are shown as lines.

DISCUSSION

For the interpretation of the observed fold distributions complete- and incomplete-fusion reaction mechanisms have been considered. To calculate fold distributions a new approach has been developed, based on Monte-Carlo simulations of entry-state population distributions as well as of the depopulation to known levels. Details of the formalism can be found in ref. [3]. In the first step the input angular momentum is calculated taking into account the dependence of the fission barrier on the angular momentum $L$. In the second step, the light-particle evaporation is simulated with Monte-Carlo
The quasidirect massive transfer process makes the massive transfer process seems to contribute to the for-

mation of light particles at large angles. At small angles the break-up process seems to contribute significantly. The particles are formed in the initial stage of the reaction before thermodynamical equi-

librium of the system is reached.

In fig. 1 the experimental fold distributions are com-
pared with simulation calculations assuming a complete fusion reaction mechanism. It can be seen that for the 2pn, α3n and α4n reaction channels the experimental fold distributions are described rather well, indicating that these reactions proceed through a complete fusion reaction mechanism. However, the fold distributions of the $^{142,143}$Eu nuclei populated in the α2n and αn reac-
tion channels, respectively, cannot be described. Fur-
thermore, the complete-fusion calculations predict very small cross sections for these channels contradictory to the experimental observation. Both facts indicate that an incomplete-fusion reaction mechanisms may play a role.

Incomplete-fusion reactions can be described as a heavy cluster stripping from the incident ion in the re-
action. They are also called “massive transfer reactions” since the remaining part of the projectile is transferred to the target nucleus and fuses with it. The direct transfer of a heavy cluster is accompanied with a considerable kinetic energy dissipation in the entrance and exit channels, defining the angular and energy distributions of the emitted particles. Semi-classical methods can be applied for the calculations of the relative motion of the parti-
cles because of the small wavelength and the high level density of excited states leading to an exhibition of the classical properties of relative motion. The transfer process, however, is not classical. Such a multi-step process provides the dominant contribution to the cross section of α-particle formation almost over the whole ranges of their energies and angles.

The mechanism of the formation of light particles in heavy-ion collision is not yet fully understood. There are several mechanisms leading to the light particle emission, the contributions of which depend on the masses and energies of the colliding nuclei and also on the energies and emission angles of the light particles. The multi-step massive transfer process seems to contribute to the for-

mation of light particles over the whole range of their energies. The quasidirect massive transfer process makes

the dominant contribution to light-particle formation at the high-energy tail of their spectrum especially at large angles. At small angles the break-up process seems to contribute significantly. The particles are formed in the initial stage of the reaction before thermodynamical equi-

librium of the system is reached.

Monte-Carlo simulation calculations of fold distributions for the α2n channel assuming an incomplete-fusion reaction mechanism have been carried out with parameters [2] describing the angular-momentum transfer, the effective barrier and the energy distributions of the α-particles. If the parameters are chosen such that cal-
culations of Zagrebaev [7] for a $^{181}$Ta($^{22}$Ne,α) reaction at 178 MeV can be reproduced, only the high-fold part of the experimental fold distribution for $^{142}$Eu can be explained as can be seen in fig. 2a. However, if the parameters are chosen such that the α-particles carry away large angular momenta then a second minimum occurs in the entry-state population distribution at low spins and the double-humped fold distribution of $^{142}$Eu can be described as shown in fig. 2b.

References: