EPJ Web of Conferences **86**, 00026 (2015)
DOI: 10.1051/epjconf/20158600026

Spin distribution as a probe to investigate the dynamical effects in fusion reactions

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Abstract. The spin distributions are measured for the compound nucleus ^{80}Sr populated in the reactions ^{16}O+^{64}Zn and ^{32}S+^{48}Ti. The comparison of the experimental results for both the systems shows that the mean γ-ray multiplicity values for the system ^{32}S+^{48}Ti are lower than those for ^{16}O+^{64}Zn. The spin distribution of the compound nucleus populated through the symmetric channel is also found to be lower than the asymmetric channel. Present investigation directly shows the effect of entrance channel mass asymmetry on the reaction dynamics.

1 Introduction

The study of light particle evaporation spectra carry important signatures of the underlying mechanism of the heavy ion induced fusion reactions. A large set of experimental data exists which has been explained in terms of the statistical model predictions. The statistical model assumes that the decay of the compound nucleus (CN) is independent of its formation. However, this assumption may not hold true always. Different studies have yielded the evidences of the dependence of the fusion dynamics on the entrance channel mass asymmetry. In some of these studies [1-3] the experimental α-particle and proton spectra for the symmetric systems were found to be softer than the statistical model predictions. The analysis of α-particle and proton spectra through dynamical model calculations, performed using HICOL [4] code, predicted that the effective l_{max} value for fusion to take place in the case of symmetric system is lower as compared to that predicted by the statistical model. These calculations also indicate that fusion for the symmetric systems are delayed which may result into some other reaction channel such as the pre-equilibrium process. The experimental neutron spectra are harder as compared to the statistical model predictions and are explained by lowering the value of level density parameter *'a'* [5, 6]. However, in most of the measurements reported in the literature, consistent analysis has not been performed by taking many other experimental observables into account. Spin distribution and cross-section measurements are also sensitive probes for the investigation of the heavy ion induced fusion dynamics. Different authors have reported the existence of entrance channel effects on the fusion dynamics using spin distribution and cross section measurement as a probe [7, 8]. With these motivations we have performed the evaporation residue (ER) cross-section (fusion cross-section) as well as ER spin distribution measurements for the asymmetric ^{16}O+^{64}Zn and symmetric ^{32}S+^{48}Ti reactions which populate the same CN ^{80}Sr. ER cross-section will provide the information of fusion dynamics, whereas ER spin distribution will give the detailed information about the contribution of different partial waves to the fusion process. The objective of the present study is to compare the ER cross-section and spin distribution of both the systems and to explain the deviations observed in the light particle spectra [3, 5]. The spin distribution measurements have been performed using the γ-ray multiplicity technique. Present article reports the preliminary results of the spin distribution measurement for the above two systems.

2 Experimental details

The experiment was performed using Heavy Ion Reaction Analyzer (HIRA) [9] + BGO multiplicity filter [10] facility at IUAC, New Delhi. Pulsed beam of ^{16}O with pulse separation of 2 μs (in the energy range from 66.6 to 83.1 MeV) and ^{32}S with pulse separation of 1 μs (in the energy range from 95 MeV to 125 MeV) were bombarded on isotopic enriched targets of ^{64}Zn and ^{48}Ti respectively. The thickness of both targets was ~ 500μg/cm^2. The targets were placed at the center of the

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target chamber. For monitoring the elastically scattered beam particles, two Si surface barrier detectors were kept inside the target chamber at ± 25° with respect to the beam direction and at a distance of 10 cm from the target position. Spin distribution measurements were performed with 14 element BGO multiplicity array placed in a close geometry. 7 detectors were placed above and 7 below the target chamber at a distance of 24 mm from the target. Each crystal of the array has a hexagonal shape with dimensions of 38 mm × 75 mm. To ensure the uniform efficiency for all the detectors, the central detectors were pulled outwards. The array covered 48% of 4π solid angle. The possibility of the attenuation of *γ*-rays in the target ladder was prevented by rotating the target ladder by 45° with respect to the beam direction and about a horizontal axis. The focal plane detector system in the present experiment was a MWPC with an active area of 6”×2” [11] and it consists of five wire electrode geometry namely, two cathodes sandwiching two position electrodes and a central anode.

3 Data Analysis and Results

The γ-ray fold distribution was generated offline, from the 14 Time to Digital Converter (TDC) signals, using CANDLE [12] software. A Time-of-Flight (TOF) spectrum was generated using anode of MWPC as start and RF as stop. Further, a two dimensional plot was generated using TOF and energy loss signal (cathode signal) of MWPC. It provides a clean separation of ER events from beam-like components. The raw γ-ray fold spectrum was gated with ER events to reject the contribution from the other events (see Fig. 1).

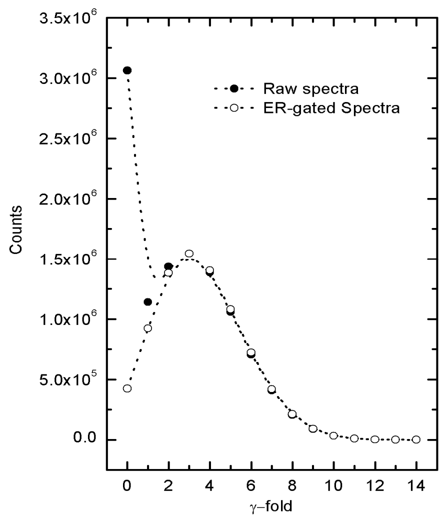

Figure 1. Comparison of Raw and ER-gated spectra for the $^{16}O+^{64}Zn$ system at E_{lab}=77.8 MeV.

3.1. Conversion to γ-multiplicity distributions

Experimentally obtained ER-gated *γ*-ray fold distributions have been unfolded to corresponding *γ*-ray multiplicity distribution using the Van Der Werf prescription [13]. According to this prescription, if *N* represents the number of identical detectors in the array and *Ω* is the efficiency of each detector, then the probability that a cascade of M_γ uncorrelated *γ*-rays will cause *p* out of *N* detectors to fire is given by

$$P_{N_p}^{M_\gamma} = \begin{pmatrix} N \\ p \end{pmatrix} \sum_{l=0}^{p} (-1)^{p-l} \begin{pmatrix} p \\ l \end{pmatrix} \left[1-(N-l)\Omega\right]^{M_\gamma} \quad (1)$$

Where, $\begin{pmatrix} N \\ p \end{pmatrix}$ denotes the number of ways *p* detector combinations are possible out of *N* detectors. Further, if the probability of observing a *p*-fold coincidence or the fold probability is denoted by *P(p)*, then it can be related to the *γ*-ray multiplicity probability distribution $P(M_\gamma)$ as follows

$$P(p) = \sum_{M_\gamma}^{\infty} P_{N_p}^{M_\gamma}(\Omega)\, P(M_\gamma) \quad (2)$$

In practice the summation varies from 0 upto the maximum value of M_γ. Since there is no direct method to generate the *γ*-ray multiplicity distribution $P(M_\gamma)$, therefore, $P(M_\gamma)$ can only be estimated in an approximate way. The simplest method is by parameter fitting, assuming a simple shape of the distribution described by a standard mathematical function. We have assumed the multiplicity distribution as a modified Fermi function of the form

$$P(M_\gamma) = \frac{2M_\gamma + 1}{1+\exp(\frac{M_\gamma - M_{\gamma 0}}{\Delta M_\gamma})} \quad (3)$$

Where, $M_{\gamma 0}$ and ΔM_γ are two free parameters that are varied to best fit the experimental *P(p)* using chi-square minimization technique. The comparison of the fitted fold distributions and extracted multiplicity distributions for both the systems at E^* = 66 MeV is shown in Fig. 2. The comparison of *γ*-ray multiplicity distribution for both the systems shows that the mean *γ*-ray multiplicity ($\langle M_\gamma \rangle$) for the symmetric system is lowered as compared to the asymmetric system. Similar results are observed for the other energies also.

3.2 Calculation of moments of γ-multiplicity distribution

The *γ*-ray multiplicity probability distribution is often characterized by its moments. The first three moments correspond to the central tendency, dispersion and degree of departure from symmetry. From the *γ*-ray multiplicity distribution, the moments of distribution can be evaluated as

$$\mu_i = \sum_{M=0}^{\infty} M^i P(M) \quad (4)$$

Where, summation varies from 0 up to the maximum value of M_γ, in practice.

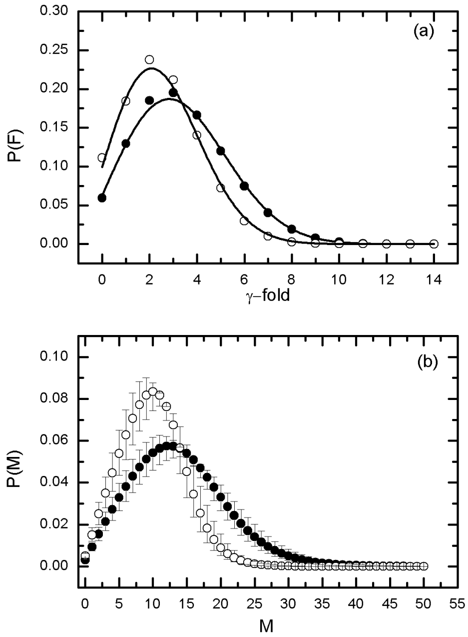

Figure 2. (a) Comparison of fitted *γ*-ray fold distributions for both the systems at E^* = 66 MeV. Black circles are the experimental data for the system $^{16}O+^{64}Zn$ and the solid line corresponds to the fitted folds. Open circles are the experimental data for the system $^{32}S+^{48}Ti$ and the dotted line corresponds to the fitted folds. (b) Comparison of extracted *γ*-ray multiplicity distribution for both the systems.

Alternate method for finding moments is as follows. The *p*-fold coincidence or the fold probabilities *P(p)* can be expressed in terms of the factorial moments as given below

$$P(p)=\sum_{m=0}^{\infty}\left[\left\langle\binom{M_\gamma}{m}m!\right\rangle\right]A_{pm}(\Omega) \qquad (5)$$

Where

$$A_{pm}(\Omega)=\frac{(-1)^m}{m!}\binom{N}{p}\sum_{l=0}^{p}(-1)^{p-l}\binom{p}{l}(N-l)^m\Omega^m \qquad (6)$$

A_{pm} is a matrix of dimension *(N* + 1*)* × *(N* + 1*)*. From Eq. 5, we get

$$\left\langle\binom{M_\gamma}{m}m!\right\rangle=\sum_{p=0}^{N}A_{mp}^{-1}P(p) \qquad (7)$$

Using this equation factorial moment can be extracted and converted to corresponding raw moments. The first raw moment gives the mean of the distribution. The values of $\langle M_\gamma \rangle$ calculated by both of these methods are found to be in agreement within error bars. Fig. 3 shows the values of $\langle M_\gamma \rangle$ as a function of E_{CM} - V_B for both the

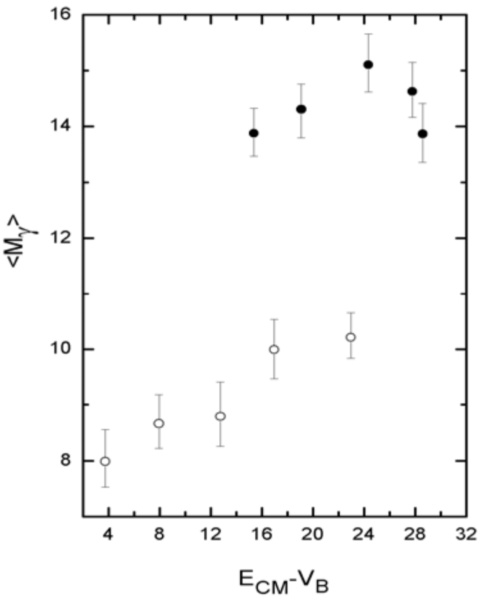

Figure 3. Comparison of mean *γ*-ray multiplicity for the two systems (black circles for $^{16}O+^{64}Zn$ and open circles for $^{32}S+^{48}Ti$) plotted as a function of E_{CM}-V_B.

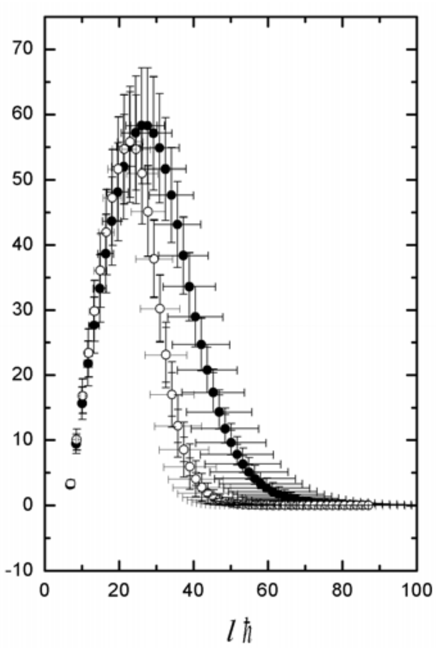

Figure 4. Comparison of experimentally extracted spin distribution for both the systems at E^* = 66 MeV. Black circles are the experimental data for the system $^{16}O+^{64}Zn$ and the open circles are the experimental data for the system $^{32}S+^{48}Ti$.

systems. These observations again indicate that for the symmetric system the $\langle M_\gamma \rangle$ are less as compared to the asymmetric system. The mean value of spin, $\langle L \rangle$, populated in the CN can be obtained from $\langle M_\gamma \rangle$ using the relation,

$$\langle L\rangle=\langle M_\gamma-\langle M_{\gamma S}\rangle\rangle\langle\Delta L_{\gamma NS}\rangle+\langle M_{\gamma S}\rangle\langle\Delta L_{\gamma S}\rangle+\langle M_n\rangle\langle\Delta L_n\rangle+\langle M_p\rangle\langle\Delta L_p\rangle+\langle M_\alpha\rangle\langle\Delta L_\alpha\rangle \qquad (8)$$

where $<M_{\gamma S}>$, $<M_n>$, $<M_p>$, $<M_\alpha>$ are the average multiplicities of statistical γ-rays and evaporated neutrons, protons and α-particles respectively. $<\Delta L_{\gamma NS}>$, $<\Delta L_{\gamma S}>$, $<\Delta L_n>$, $<\Delta L_p>$, $<\Delta L_\alpha>$ are the corresponding values of average angular momentum carried by each type of transition. The value of $<\Delta L_{\gamma NS}>$ for the present systems was taken to be 1.6. This value was obtained using the level schemes [14] of the different ERs populated in the reactions under study. The values of other parameters were obtained from the statistical model calculations. Assuming that the Eq. 8 is true for the distribution also, we have obtained the spin distribution of the CN from the γ-ray multiplicity distribution. The spin distributions for both the systems at E^* = 66 MeV are compared in Fig. 4. It is observed that the spin distribution for the symmetric system is lower than the asymmetric system. Similar results were obtained at other energies also. The theoretical spin distributions have been obtained by performing a simplified coupled channel calculation using the CCDEF code [15]. The comparison of the experimental spin distributions with the theoretical spin distributions showed that the experimental spin distributions for the asymmetric system are in agreement with the CCDEF calculations but for the symmetric system the experimental spin distributions are lower than the theoretical predictions.

4 Conclusions

The comparison of first moment of ER γ-ray multiplicity $<M_\gamma>$, for two different entrance channels populating the same CN shows that the values for the symmetric system are lower than the asymmetric system. The spin distributions of the CN populated in both the systems were obtained by adding back the contribution of each type of transition before the γ-ray emission. The spin distributions of the symmetric system were found to be lower than the asymmetric system. The comparison with the spin distribution generated by the CCDEF code also shows that the spin distribution of the symmetric system is less than the theoretical predictions. These observations clearly indicate the non fusion of higher partial waves for the symmetric system. Similar observations of the non fusion of the higher partial waves have been reported earlier through the charged particles evaporation spectra studies [3]. It is conjectured that the higher partial waves that are not contributing to the formation of an equilibrated CN may result in some other reaction channel such as the pre-equilibrium process. The existence of the pre-equilibrium process for the present systems has also been reported through the analysis of neutron spectrum [5].

The cross-section measurements for these systems have also been performed in the same energy range and the analysis is in progress. Though the simplified coupled channel calculations have already been performed using the CCDEF code, we aim at fitting the experimental cross-sections using the CCFULL code [16] and the generated spin distributions will be used to explain the experimental spin distributions. Further, we would use the experimentally generated spin distribution to explain the deviations observed in the light particle evaporation spectra from the statistical model predictions for the case of symmetric systems [3, 5].

Acknowledgement

The financial assistance from the University Grants Commission (UGC), India to one of the authors (M.K.) is gratefully acknowledged.

References

1. I.M. Govil, R. Singh, A. Kumar, Ajay Kumar, G. Singh, S.K. Kataria and S.K. Datta, Phys. Rev. C **62**, 064606 (2000).
2. J. Kaur, I.M. Govil, G. Singh, Ajay Kumar, A. Kumar, B.R. Behera and S.K. Datta, Phys. Rev. C **66**, 03460 (2002).
3. J. Kaur, A. Kumar, Ajay Kumar, G. Singh, S.K. Datta and I.M. Govil, Phys. Rev. C **70**, 017601 (2004).
4. H. Feldmeier, Rep. Prog. Phys. **50**, 915 (1987).
5. Ajay Kumar, A. Kumar, G. Singh, B.K. Yogi, Rakesh Kumar, S.K. Datta, M.B. Chatterjee and I.M. Govil, Phys. Rev. C **68**, 034603 (2003).
6. Ajay Kumar, A. Kumar, G. Singh, Hardev Singh, R.P. Singh, Rakesh Kumar, K.S. Golda, S.K. Datta and I.M. Govil, Phys. Rev. C **70**, 044607 (2004).
7. Gayatri Mohanto, N. Madhavan, S. Nath, Jhilam Sadhukhan, J. Gehlot, I. Mazumdar, M.B. Naik, E.Prasad, Ish Mukul, T. Varughese, A. Jhingan, R.K. Bhowmik, A.K. Sinha, D.A. Gothe, P.B. Chavan, Santanu Pal, V.S. Ramamurthy, A. Roy, Nucl. Phys. A **890**, 62 (2012).
8. P.D. Shidling, N. Madhavan, V.S. Ramamurthy, S. Nath, N.M. Badiger, S. Pal, A.K. Sinha, A. Jhingan, S. Muralithar, P. Sugathan, S. Kailas, B.R. Behera, R. Singh, K.M. Varier, M.C. Radhakrishna , Phys. Lett. B **670**, 99 (2008).
9. A.K. Sinha, N. Madhavan, J.J. Das, P. Sugathan, D.O. Kataria, A.P. Patro and G.K. Mehta, Nucl. Instr. and Meth. A **339**, 543 (1994).
10. S. Muralithar, DAE symp. on Nucl. Phys. **34** B, 417 (1991).
11. Akhil Jhingan, P. Sugathan, Ranjeet Dala, T. Varughese, H. Singh, J. Gehlot, S. Nath, J.J. Das, N. Madhavan, R.P. Singh, P. Shidling, B.R. Behera and S.K. Mandal, in Proc. of the DAE Symp. Nucl. Phys. **52**, 585 (2007).
12. E.T. Subramaniam, B.P.A. Kumar, and R.K. Bhowmik (unpublished).
13. S.Y. Van Der Werf, Nucl. Instr. and Meth. **153**, 221 (1978).
14. http://www.nndc.bnl.gov/.
15. J. Fernandez Niello, C. H. Dasso, and S. Landowne, Comput. Phys. Commun. **54**, 409 (1989).
16. K. Hagino, N. Rowley and A. T. Kruppa, Comput. Phys. Commun. **123**, 143 (1999).