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Broad structures in γ-ray multiplicity gated p and α spectra in low energy ^{12}C+^{93}Nb and ^{16}O+^{89}Y reactions

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Abstract. Gamma ray multiplicity gated proton spectra have been measured in the reactions ^{12}C+^{93}Nb at E(^{12}C)= 40 and 45.5 MeV and ^{16}O+^{89}Y at E(^{16}O)= 51 and 54 MeV populating the CN ^{105}Ag at E_X between 35 and 40 MeV. Broad structures are seen in all spectra at high gamma ray multiplicities. The present data, along with those from our earlier work on the former reaction at E(^{12}C)= 42.5 MeV, establish the compound nuclear origin of the structures. The data can be explained by incorporating a localised enhancement of nuclear level density in the excitation energy and angular momentum space. Multiplicity gated α spectra have also been measured in the same reaction at E(^{12}C)= 37.5 − 45 MeV. Broad structures seen in these spectra seem to have contribution from other reaction mechanisms also.

1 Introduction

In low energy heavy ion reactions light particles are emitted predominantly from the compound nuclear (CN) evaporation process. Spectra of charged particles like proton and α have a broad maximum near the Coulomb barrier and fall monotonically at higher particle energies. The spectral shape at high particle energies is governed by the variation of nuclear level density (NLD) with excitation energy (E_X) and angular momentum ($J\hbar$) in the residual nucleus. While addressing this issue in our earlier works, we observed unusual broad structures in γ-ray multiplicity gated proton spectra in the ^{12}C+^{93}Nb reaction at E(^{12}C)= 40 and 42.5 MeV [1,2]. These are in gross contradiction to the predictions of the statistical model (SM) incorporating the conventional E_X and J-dependence of NLD [3]. An empirical prescription of a localised enhancement of NLD in (E_X, J) space explained the data. The proposed enhancement damps beyond a certain critical value of E_X above the yrast line and below a certain critical J. In a radically different approach, the structures were described as due to a massive cluster transfer forming a doorway configuration of ^{11}B + ^{93}Nb in ^{104}Pd in a certain E_X and J range. If the broad structures have a CN origin, the proton spectral shape in the centre of mass (CM) system should be independent of entrance channel and the angular distribution should show a symmetry around 90°. With this motivation the present work describes our measurements of proton spectra in the ^{12}C+^{93}Nb and ^{16}O+^{89}Y reactions, forming the same CN ^{105}Ag, at various beam energies and detector angles. Finally, α spectra have also been measured in the ^{12}C+^{93}Nb reaction at three beam energies in order to address the exit channel dependence of the observed structures.

Table 1. Nuclear reactions reported in this paper.

Reaction	E_{beam} (MeV)	E_X^{CN} (MeV)	Measurment	Spectra
^{16}O+^{89}Y	54.0	39.8	present	p
^{12}C+^{93}Nb	45.5	39.8	present	p
^{16}O+^{89}Y	51.0	37.5	present	p
^{12}C+^{93}Nb	42.5	37.5	earlier	p
^{12}C+^{93}Nb	40.0	34.9	present	p
^{12}C+^{93}Nb	37.5	32.7	present	α
	40.0	34.9	present	α
	45.0	39.4	present	α

2 Experimental Details

Experiments were performed at the 14UD BARC-TIFR Pelletron accelerator in Mumbai using ^{12}C and ^{16}O beams at different energies (see Table 1) bombarding self supporting rolled ^{93}Nb and ^{89}Y targets (∼ 99.9% purity) of thickness ∼ 0.5 mg/cm^2. Additional targets of C (∼ 50 μg/cm^2) and Ta_2O_5 (∼ 1 mg/cm^2 backed by ∼ 2 mg/cm^2 Ta) were used to assess the contribution of background from O and C impurities in the Nb and Y targets. Protons were detected in NaI(Tl) scintillation detectors (4.4 cm $\phi\times$ 3.8 cm thick) placed at a distance of ∼14 cm from the target. In the first three cases (Table 1) the detectors were kept at angles

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of 116°, 125° and 153° with respect to the beam direction. In the fifth case, two detectors were used at 52.5° and 122.5°. All the detectors had an 8 μm thick havar entrance window and were covered in front with a tantalum foil of thickness $\sim$ 47 mg/cm^2 in order to stop the beam like particles. Measurement on α particles were performed with two $\triangle$E - E telescopes mounted at 116° and 153° and at a distance of $\sim$7 cm from the target. The E detectors were 5 mm thick Si(Li) detectors of surface area (S) 500 mm^2. The $\triangle$E detectors were silicon detectors of S $\sim$ 450 mm^2 and 50-60 μm thick. The multiplicity of low energy γ rays in coincidence with the particles were measured using a 14 BGO detector setup [1]. The total efficiency of the multiplicity setup in various experimental runs was 56 - 59% for 662 keV γ rays. The energy calibration of NaI(Tl) detectors was performed by measuring the elastically scattered protons of energies ranging from 10 to 24 MeV from ^{209}Bi and C targets. The Si(Li) detectors were calibrated for E_α upto 8.4 MeV using ^{241}Am+^{239}Pu and ^{229}Th alpha sources. Standard pulse shape discrimination (PSD) technique was employed to separate protons from gamma rays and alpha particles in the NaI(Tl) detectors. Alpha particles were separated from protons in $\triangle$E - E telescopes by the difference in their energy loss in $\triangle$E detectors.

The number of BGO detectors in prompt coincidence (within $\sim$50 ns) with the charged particle detectors, henceforth defined as fold (F), was measured for each event. The proton and α spectra for each fold were extracted for the various reactions after correcting for the energy loss of protons in the tantalum foil and havar window and of alpha particles in the ΔE detectors. The background (from C and O) corrected F-gated proton and α spectra at different angles were converted to energy differential cross sections in the CM frame. The shapes of the F-gated CM proton spectra at various angles were similar within ±15% and, hence, the cross sections were averaged at each energy. The final energy differential cross sections are reasonable representations of the angle integrated cross sections. The spectra show broad structures at high folds as seen in Fig. 1. The energy dependent cross sections for alpha particles differ up to ±50% at the two angles where measurements were made. However, the shapes of the CM spectra are similar, showing prominent broad structures at both the angles, as seen in Fig. 2.

3 Results and Discussion

3.1 Proton spectra

One of the main motivations in the present study was to investigate the structures in proton spectra in two different reactions producing the same CN at a similar E_X^{CN}. Fig. 1 shows examples of proton spectra at high folds (F=6-8) from ^{16}O + ^{89}Y and ^{12}C + ^{93}Nb reactions producing ^{105}Ag at E_X^{CN} of 37.5 and 39.8 MeV. The shapes of the spectra are indeed very similar for different entrance channels at a given E_X^{CN}. In order to quantify the observations, statistical model analysis was done for all the spectra.

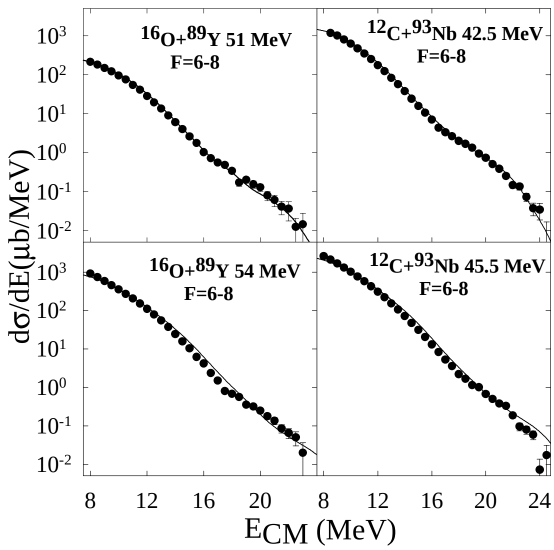

Fig. 1. Experimental proton spectra and the statistical model fits with enhanced NLD prescription (see text) for various reactions shown for F=6- 8 window.

The procedure described in our earlier works [2] was used for the SM calculation of fold gated particle spectra after suitable modifications in CASCADE [4]. The phenomenological form of NLD prescribed by Ignatyuk et al. [3] was used in the present analyses. This is given as

$$\rho(E_X, J) \sim \frac{(2J+1)\sqrt{a}}{U^2} exp(2\sqrt{aU}), \quad (1)$$

where

$$U = E_X - E_{rot} - \Delta_P, \quad (2)$$

$$E_{rot} = \frac{\hbar^2}{2\Im} J(J+1) \quad (3)$$

and

$$a = \tilde{a}\left[1 - \frac{\Delta_S}{U}\{1 - exp(-\gamma U)\}\right]. \quad (4)$$

The physical significance of the parameters a, $\tilde{a} = A / \delta a$, $\gamma(= 0.054 \text{ MeV}^{-1})$, Δ_P, Δ_S and $\Im$ are explained in Refs. [1–3]. The probability distribution of angular momentum in CN is given by

$$P(l) \sim \frac{(2l+1)}{1 + exp[(l - l_0)/\delta_l]}. \quad (5)$$

Here $l\hbar$ is orbital angular momentum in the incident channel and δ_l is diffuseness parameter. The fusion cross section (σ_{fus}) decides the value of critical angular momentum ($l_0\hbar$). The values of the input parameters used in CASCADE calculations are given in Table 2.

The conventional SM calculations show a monotonic fall and fail to reproduce the structures. The

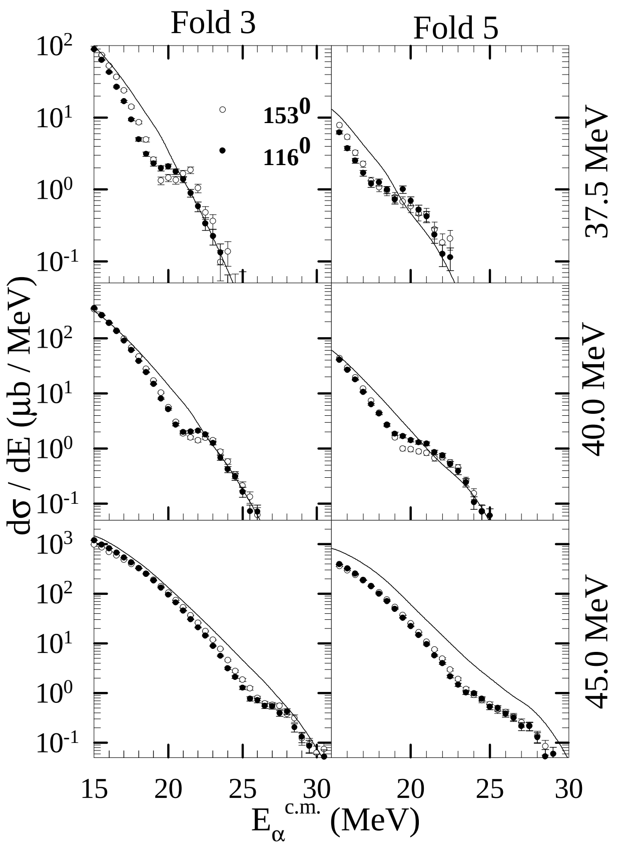

Fig. 2. Experimental alpha spectra and SM fits with enhanced NLD prescription at the angles and beam energies shown in the figure.

Table 2. Input and output parameters for the SM calculation of fold gated proton spectra with CASCADE. E_X^{CN} and δa are in MeV and σ_{fus} in mb. J_C^{max} represents J - value at which angular momentum distribution of the CN is peaked.

Reaction	E_X^{CN}	σ_{fus}	δ_l	δa	l_0	J_C^{max}
$^{16}O+^{89}Y$	39.8	270	2.5	8.1	15.0	12.5
$^{16}O+^{89}Y$	37.5	175	2.5	8.3	12.0	9.5
$^{12}C+^{93}Nb$	39.8	510	2.0	8.2	18.0	13.5
$^{12}C+^{93}Nb$	37.5	324	3.0	8.6	13.5	10.5

calculations were repeated with the prescription of enhanced NLD described as follows. The conventional NLD (Eq. 1) was multiplied by an enhancement function

$$\varepsilon(E_X, J) = 1 + Kf(E_X)g(J), \qquad (6)$$

where

$$f(E_X) = exp[-\frac{(U-E_c)^2}{2\sigma_X^2}], \qquad U > E_c \qquad (7)$$
$$= 1, \qquad U < E_c$$

Table 3. Best fit parameters for fold gated proton spectra with enhanced NLD prescription. E_X^{CN}, E_c, p and q are in MeV.

Reaction	E_X^{CN}	K	E_c	p	q	J_c	Δ_J
$^{16}O+^{89}Y$	39.8	30	3	3.5	0.06	18	3
$^{16}O+^{89}Y$	37.5	35	3	3.5	0.06	18	3
$^{12}C+^{93}Nb$	45.1	30	3	3.5	0.06	18	3
$^{12}C+^{93}Nb$	37.5	30	3	3.5	0.06	18	3

with U as defined in Eq.(2) and

$$g(J) = exp[-\frac{(J-J_c)^2}{2\sigma_J^2}], \qquad J < J_c \qquad (8)$$
$$= 1, \qquad J > J_c.$$

The full width at half maxima corresponding to σ_J and σ_X are denoted by Δ_J and a J dependent $\Delta_E = p$ - qJ. The fold gated spectra were calculated for various reactions with the input parameters shown in Table 3. The solid lines in Fig. 1 show the results of the calculations for the fold window 6-8. Almost the same enhancement parameters reasonably describe the spectra establishing in a quantitative manner that the appearance of the broad structures is independent of the entrance channel and hence the structures are to be attributed to the CN origin.

Fig. 3 shows the measured CM spectra in the reaction ^{12}C + ^{93}Nb at E(^{12}C)= 40 MeV, for F>5, at the laboratory angles of 52.5° and 122.5° which corresponds to CM angle of ∼55° and 125° for the protons in the broad structure regime. The lower panel shows the ratio of the cross sections. For the high fold spectra the background subtraction from the C and O impurities (more important at forward angle) could be made with high level of confidence. The overlap of the spectra for the two angles establish the symmetry about the CM angle of 90°. This observation further supports the CN origin of the structures.

These results strongly suggest an enhancement in NLD very near the yrast line in the nuclei studied. More experiments are required to see if this is a generic feature or special to a particular mass region. It may be added that the collective enhancement in NLD has been proposed earlier in the context of neutron resonances in rare earth nuclei [5] and the fragment mass distributions in the ^{238}U+Cu reaction at 950 MeV per nucleon [6].

3.2 Alpha particle spectra

The experimental α spectra for two folds are shown in Fig. 2. The SM calculations with the enhancement in the NLD are shown by the solid lines. The enhancement parameters are the same as those in Table 3. The results indicate that the shape of the experimental cross sections cannot in general be reproduced except for the appearance of a broad structure at high

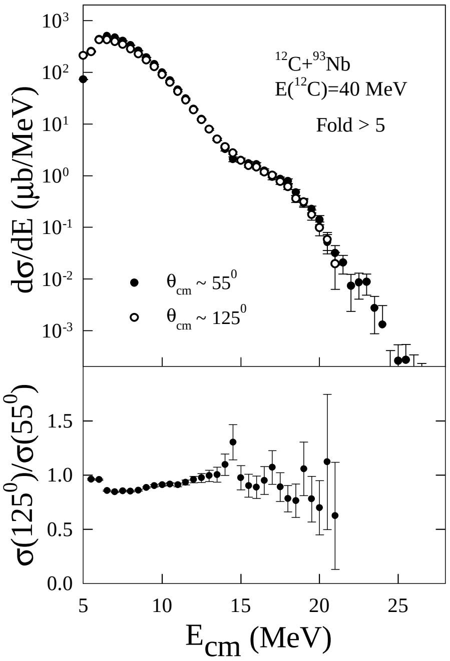

Fig. 3. Experimental proton spectra at two angles symmetric about 90° in CM system and their ratio in the reaction and fold window shown in the figure.

folds. However, the experimental spectra show prominent structures at low folds also. It may be mentioned that our recent measurement of inclusive alpha particle spectra [7] in the same reaction show a large discrepancy from the SM calculation even near the evaporation bump region ($E_\alpha = 7$ to 15 MeV). It is possible, therefore, that other mechanisms contribute significantly to the alpha particle spectra. A possible mechanism is α-transfer to the target nucleus followed by the break-up of the ^{8}Be ejectile formed both in the ground and excited states. These break-up alpha particles can reach the detector producing the shift of the apparent evaporation bump (mainly from the ground state ^{8}Be decay) and also a wide distribution (mainly from the decay of excited ^{8}Be) which added to the SM process can look like a broad structure at the high energy region. Considering these aspects, it is difficult to make any quantitative statement regarding the enhancement of NLD from these alpha spectra.

4 Summary

In summary, gamma ray multiplicity gated proton and alpha particle spectra were measured in the ^{12}C and ^{16}O induced reactions on ^{93}Nb and ^{89}Y targets at various beam energies. These spectra show broad structures which are more prominent at higher γ-ray multiplicity. The proton spectra from ^{12}C+^{93}Nb and ^{16}O+^{89}Y reactions producing the compound nucleus ^{105}Ag at same excitation energies have similar shapes. The spectra measured in ^{12}C+^{93}Nb reaction at the 40 MeV beam energy show symmetry about 90° in the centre of mass system. These observation support the compound nuclear origin of the structures which can be understood within the statistical model with an enhanced (E_X, J) dependent NLD. The enhancement parameters are similar for all the cases.

The statistical model including enhanced NLD is not very successful in explaining the γ-ray multiplicity gated alpha particle spectra. This could be due to significant contributions from other processes which make the extraction of the excitation energy and angular momentum dependence of NLD difficult from alpha particle spectra.

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