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Unusual features of proton and α-spectra from low-energy heavy-ion reactions

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Abstract. Proton and α-particle spectra have been measured in low-energy ^{12}C and ^{16}O-induced reactions on Nb and Y targets with the primary aim of measuring the excitation energy and angular momentum dependence of nuclear level density. In the γ-multiplicity gated spectra, an unusual feature of a broad structure at high particle energies is observed in all the cases. In the case of proton spectra, the structures have compound nuclear origin and point towards an excitation energy and angular momentum-dependent enhancement which is beyond the conventional level density prescription. The broad structures in the α-spectra cannot be fully explained within the statistical model even with the enhanced level density. In this case, other reaction mechanisms like the transfer of α or ^{8}Be to the target could also be important.

Keywords. Proton and α-spectra; heavy-ion reaction; broad structures; nuclear level density.

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1. Introduction

Proton and α-particle spectra following heavy-ion reactions have been measured for a variety of projectile–target combinations since the advent of heavy-ion accelerators. For low bombarding energies, typically <8 MeV per nucleon, the spectra can be explained as mainly due to the evaporation from an equilibrated compound nucleus (CN) formed in the fusion reaction. Two important physical inputs in the statistical model calculations describing the spectra are the transmission through the Coulomb barrier (CB) and the excitation energy (E_{X}) and angular momentum ($J\hbar$) dependence of nuclear level density (NLD). The transmission coefficient through the CB depends on the barrier height and is influenced by the nuclear shapes formed in the fusion reaction. The effects of angular momentum and temperature-dependent shape evolution and fluctuations on the particle spectra have been addressed in a series of measurements over many years [1]. These aspects are generally important at high excitation energies and angular momenta. At low excitation energies and not too high angular momenta, where the shape change is not very significant, the measurements can provide reliable information on the E_{X} and J dependence of the NLD.

Nuclear level density [2–4] is a very important physical quantity not only from the fundamental point of view of understanding a many-fermion quantum system but also for its application. Many theoretical methods have been adopted for the calculation of the NLD. One method is statistical in terms of the partition function and was originally utilized [2,3] assuming a constant spacing in the single-particle energies. An analytic form of the dependence of NLD on the excitation energy and angular momentum was derived with some further approximations. The simplistic picture was later modified to incorporate the surface effects, the pairing and shell effects, collective enhancement etc. from a semi-empirical phenomenological approach [4]. There are many other theoretical methods based on more microscopic approaches [5]. The experimental measurement of the NLD over a wide range of E_{X} and J is a basic necessity to test any of these theoretical calculations.

The scenario of the experimental measurements of the NLD is far from complete. Various measurements are reported based on neutron and charged particle capture resonances [6], Ericson fluctuation analysis of compound nuclear reactions [7], γ-ray spectral measurements following the inelastic and transfer reactions [8] etc. In all these, the ranges of E_{X} and/or J are not high. Measurement of particle spectra in heavy-ion reactions [4] has the potential to extend both E_{X} and J ranges. In many of these measurements, an average information is extracted since the particles are emitted in a multistep process spanning a range of excitation energies and nuclei.

We have been pursuing a program of the measurement of proton and α-spectra in low-energy heavy-ion reactions with the primary motivation of measuring the E_{X} and J dependence of NLD. In our low bombarding energy regime (typically <5 MeV per nucleon), the statistical model of evaporation can be confidently applied to describe the spectra. The NLD information is extracted from the high-energy part of the particle spectra for which the uncertainty in the calculation of transmission coefficient is small. The selection of low E_{X} in the CN and the high particle energy ensures that the first step decay from the CN contributes predominantly. Therefore, the NLD of a specific nucleus is addressed instead of that of an ensemble average. These conditions are not satisfied for a wide variety of target–projectile combinations. The excitation energy range is also restricted typically up to $\sim$25 MeV. However, many nuclear structure effects are manifested in this range making this an interesting regime of study.

The first phase of our program was on the inclusive proton spectra from which we extracted the E_{X} dependence of the total (J-summed) NLD for some nuclei [9,10]. In the measurements on the J-dependence of the NLD, derivable from the spectra measured in coincidence with γ-ray multiplicity (a quantity related to J), we were confronted with some unusual observations. Departing from the expected monotonically decreasing cross-section with proton kinetic energies (as seen in the inclusive spectra), broad structures were observed [11,12] at high γ-ray multiplicity. This paper is concerned with these observations and their possible interpretation.

2. Experimental methods and earlier observations

The experimental measurements to be described in this paper were performed with ^{12}C and ^{16}O beams bombarding ^{93}Nb and ^{89}Y targets in the Mumbai Pelletron.

The beam energy range was from 37 to 54 MeV. The monoisotopic, self-supporting and chemically pure (better than 99%) targets were typically 0.5 mg/cm^2 thick and prepared by rolling. Proton and α-particle spectra were measured with NaI(Tl) scintillation detectors and silicon ΔE–E telescopes, respectively, placed at suitable angles and distances. The contributions to the spectra from the carbon and oxygen impurities were subtracted by measuring with suitable carbon and oxygen targets. The γ-ray multiplicity was measured in an array of 14 bismuth germanate (BGO) detectors arranged in two close-packed groups of seven. The efficiency of the array ranged from ∼55 to 60% for 662 keV γ-ray. The other details of the measurements are described in [11–13].

As mentioned in the Introduction, in our earlier measurements [11,12] of fold-gated centre of mass (c.m.) proton spectra in the $^{12}\text{C} + {}^{93}\text{Nb}$ reaction at $E(^{12}\text{C}) =$ 40 and 42.5 MeV, we observed broad structures at high folds. Here fold means the number of BGO detectors simultaneously producing electronic signals following the detection of low-energy γ-rays. The structures were also observed in an exclusive measurement in coincidence with the fusion residue γ-rays further establishing that their origin is not from target impurities. The structures were more prominent at higher folds and lower bombarding energies. For a given beam energy, the mean energy of the structure was seen to decrease with fold whereas for a given fold, it was seen to go up with beam energy.

Assuming that the observed broad structures have a compound nuclear origin, a comparison of the measured spectra with the statistical model calculation for the evaporation from a compound nucleus was made. In this calculation, the phenomenological prescription of the NLD, as mentioned in the Introduction, was used. The prescription included the shell effect and its damping with excitation energy following the formulation of Ignatyuk *et al* [14]. The E_{X} and J dependence of the NLD were taken as

$$\rho(E_{\mathrm{X}}, J) \sim \frac{(2J+1)\sqrt{a}}{U^2} \exp(2\sqrt{aU}), \tag{1}$$

where

$$U = E_{\mathrm{X}} - E_{\mathrm{rot}} - \Delta_{\mathrm{P}}, \tag{2}$$

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

Here Δ_{P} is the pairing energy and $\Im$ is the moment of inertia. The energy-dependent NLD parameter a, given by

$$a = \tilde{a}\left[1 - \frac{\Delta_{\mathrm{S}}}{U}\{1 - \exp(-\gamma U)\}\right], \tag{4}$$

manifests the shell effect and its damping characterized by the shell correction Δ_{S} in mass and the parameter γ. The calculations were done using the code CASCADE [15] after suitable modifications because in its original version, the code cannot calculate the fold-gated particle spectra. Other details of the calculation can be seen in [11].

The calculated proton spectra for different folds were seen to fall monotonically with proton energy and could not describe the observed broad structures. Guided by the systematics of the structures, a possible explanation was proposed in terms of an E_{X} and J-dependent enhancement of the NLD. The conventional NLD was multiplied by an enhancement function

$$\varepsilon(E_{\mathrm{X}}, J) = 1 + K f(E_{\mathrm{X}}) g(J), \tag{5}$$

where

$$\begin{aligned} f(E_{\mathrm{X}}) &= \exp\left[-\frac{(U - E_{\mathrm{c}})^2}{2\sigma_E^2}\right], \quad U > E_{\mathrm{c}} \\ &= 1, \qquad\qquad\qquad\qquad U < E_{\mathrm{c}} \end{aligned}$$

and

$$\begin{aligned} g(J) &= \exp\left[-\frac{(J - J_{\mathrm{c}})^2}{2\sigma_J^2}\right], \quad J < J_{\mathrm{c}} \\ &= 1, \qquad\qquad\qquad\qquad J > J_{\mathrm{c}}. \end{aligned}$$

Here K denotes the enhancement factor and the full-width at half-maxima corresponding to σ_J and σ_E are denoted by Δ_J and J-dependent $\Delta_E = p - qJ$. The above form implies a uniform enhancement factor up to a certain critical energy E_{c} above the yrast plus pairing energy (corresponding to a critical temperature) and a damping in the enhancement at higher energies. In the angular momentum space, the enhancement takes place above a critical value J_{c} and damps at lower angular momenta. The calculated spectra utilizing the enhanced NLD prescription reasonably reproduced the broad features of all the fold-gated spectra. The best choices for the enhancement parameters are tabulated later along with those obtained in the recent measurements.

3. Recent measurements

The main motivation behind our recent measurements was as follows: If the observed broad structures really have a compound nuclear origin, the proton spectral shape in the c.m. system should be independent of the entrance channel and the angular distribution should be symmetric around 90°. The recent measurements were therefore made on the proton spectra in the $^{12}\mathrm{C} + {}^{93}\mathrm{Nb}$ and $^{16}\mathrm{O} + {}^{89}\mathrm{Y}$ reactions, forming the same compound nucleus $^{105}\mathrm{Ag}$, at various beam energies and detector angles. Measurements were also made in $^{12}\mathrm{C} + {}^{89}\mathrm{Y}$ reaction. Finally, α-spectra have been measured in the $^{12}\mathrm{C} + {}^{93}\mathrm{Nb}$ reaction at three beam energies in order to address the exit channel dependence of the observed structures. Table 1 gives the detailed information of the various measurements (some of which have already been reported in [13]).

3.1 *Observations on proton spectra*

The shapes of c.m. proton spectra at various angles were similar, as seen in earlier measurements also, within ±15% and, hence, the cross-sections were averaged over various angles. These average values should be reasonable representations of the angle integrated cross-sections. Figures 1 and 2 show examples of the c.m. proton spectra from the recent measurements. In all the measured spectra, broad structures with the systematic features mentioned earlier were seen.

The similarity of the spectra in two entrance channels, forming the same compound nucleus at the same $E_{\rm X}$, was apparent from the comparison of the spectra from the $^{16}{\rm O}+{}^{89}{\rm Y}$ reaction at $E(^{16}{\rm O})=54$ and 51 MeV (figure 2) with those from the $^{12}{\rm C}+{}^{93}{\rm Nb}$ reaction at $E(^{12}{\rm C})=45.5$ MeV (figure 1) and 42.5 MeV (earlier measurements), respectively. It is obvious, as also seen by actual calculations, that the statistical model calculations with the normal NLD prescription fail to reproduce the structures. The solid lines in figures 1 and 2 are the results of the

Table 1. Nuclear reactions studied in the recent measurements.

Reaction	$E_{\rm beam}$ (MeV)	$E_{\rm X}^{\rm CN}$ (MeV)	Measured spectra
^{12}C+^{93}Nb	37.5	32.7	α
	40.0	34.9	p, α
	45.0	39.4	α
	45.5	39.8	p
^{16}O+^{89}Y	51.0	37.5	p
	54.0	39.8	p
^{12}C+^{89}Y	40.0	34.5	p

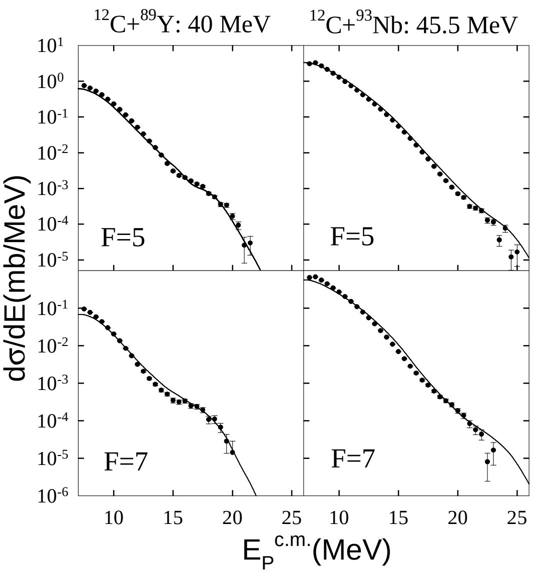

Figure 1. Fold-gated proton spectra (filled circles) for various folds F in the $^{12}{\rm C}+{}^{89}{\rm Y}$ and $^{12}{\rm C}+{}^{93}{\rm Nb}$ reactions. The solid lines are the results of statistical model calculations with the enhanced NLD prescriptions.

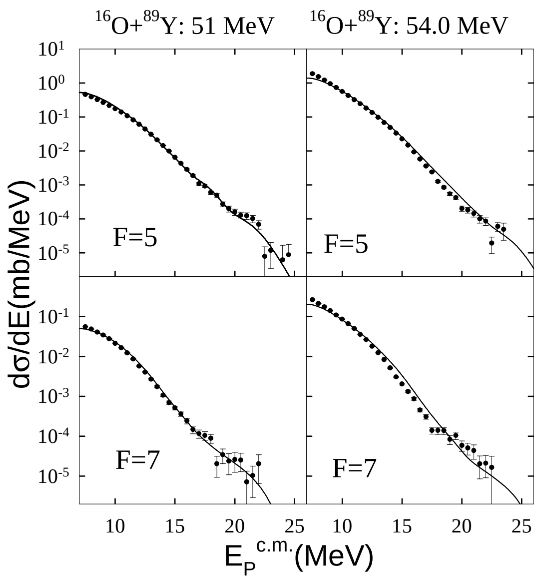

Figure 2. Same as figure 1 except that the spectra are for $^{16}O + {}^{89}Y$ reaction.

Table 2. Parameters for the enhanced NLD prescription.

Reaction	E_{beam} (MeV)	E_X^{CN} (MeV)	K	E_c (MeV)	p (MeV)	q (MeV)	J_c	Δ_J	Measurement
$^{12}C + {}^{93}Nb$	40.0	35.3	30	3	3.5	0.06	18	3	Earlier
	42.5	37.5	30	3	3.5	0.06	18	3	Earlier
	45.5	39.8	30	3	3.5	0.06	18	3	Present
$^{16}O + {}^{89}Y$	51.0	37.5	35	3	3.5	0.06	18	3	Present
	54.0	39.8	30	3	3.5	0.06	18	3	Present
$^{12}C + {}^{89}Y$	40.0	34.5	30	3.5	3	0.07	18	3	Present

calculation with the enhanced NLD prescription showing a reasonably good fit to the data. The parameters for the enhanced NLD prescription are shown in table 2 along with the values from our earlier measurements. A very similar set of enhancement parameters explains the data for both the entrance channels. This observation suggests that the structures have a compound nuclear origin.

Figure 3 shows the measured c.m. proton spectra in the ^{12}C + ^{93}Nb reaction at $E(^{12}C)$= 40 MeV, for fold $F > 5$, at the laboratory angles of 52.5° and 122.5° which correspond to c.m. angles of ∼55° and 125°, respectively, for the protons in the broad structure regime. The lower panel shows the ratio of the cross-sections. At higher folds, the background subtraction from the carbon and oxygen impurities (more important at forward angle) could be made with a high level of confidence. The observed overlap of the spectra for the two angles establish the symmetry about the c.m. angle of 90°. This observation strongly supports the compound nuclear origin of the structures.

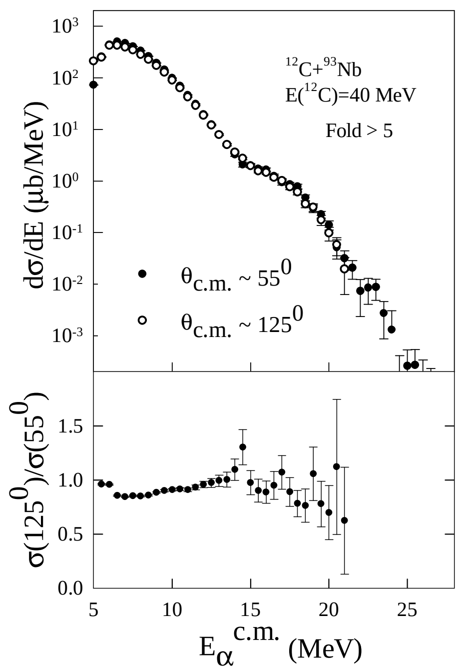

Figure 3. Experimental proton spectra at two angles symmetric about 90° in the c.m. system and their ratio in the reaction and fold window shown in the figure.

3.2 *Observations on α-spectra*

Figure 4 shows examples of the c.m. spectra for α-particles in the $^{12}\mathrm{C} + {}^{93}\mathrm{Nb}$ reaction at two angles. The energy-dependent cross-sections for α-particles differ up to $\pm 50\%$ at the angles measured. However, the shapes of the c.m. spectra are similar so far as showing a prominent broad structure at higher α-particle energies at both the angles. The statistical model calculations for fold-gated α-particle spectra were done with the enhanced NLD prescription using similar parameters as used for the proton spectra. The results shown in figure 4 indicate that the shape of the experimental cross-sections cannot be reproduced by these calculations except for the appearance of a broad structure at high folds. However, the experimental spectra show prominent structures at low folds also. Although better fits were obtained for the inclusive α-particle spectra for energies beyond 15 MeV, our earlier measurement of inclusive α-particle spectra [16] in the $^{12}\mathrm{C} + {}^{93}\mathrm{Nb}$ reaction showed a large disagreement with the statistical model calculations in the evaporation bump region ($E_\alpha = 7$–15 MeV).

4. Discussion

The compound nuclear origin of the broad structures in the proton spectra suggests that the excitation energy and angular momentum dependence of the NLD deviates

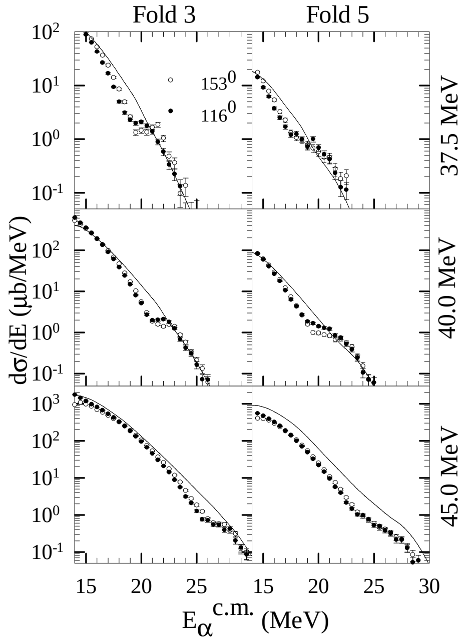

Figure 4. Experimental α-spectra at two angles and beam energies are shown in the figure. The solid lines are the results of statistical model calculations with the enhanced NLD prescription.

strongly from the conventional wisdom. Since the proton energies in the region of the broad structures correspond mainly to those from the first step emission from the compound nucleus, we are addressing the NLD in a specific nucleus having the atomic and mass numbers one less than that of the compound nucleus. In this regard and to our knowledge, this is the first direct measurement of the excitation energy and the angular momentum dependence of the NLD in a specific nucleus. Our empirical prescription of the modified NLD consistently describes the unusual features of the spectra in a variety of reactions and bombarding energies with very similar parameters. These results strongly suggest that an enhancement in NLD near the yrast line is the explanation for the observed broad structures. More experiments are, of course, required to see if this is a generic feature or special to the particular mass region studied in this work.

In the normal phenomenological NLD formula used in the present calculations, the collective enhancement is not included. The collective enhancement has been proposed earlier in the context of the NLD in rare-earth nuclei [3] and the fragment mass distributions in the $^{238}\mathrm{U}+\mathrm{Cu}$ reaction at 950 MeV per nucleon [17]. The enhanced NLD, required to explain the broad structures in this work, could be ascribed to the collective enhancement. In a recent series of papers, the calculation of the NLD from a combinatorial approach has been done including the rotational and vibrational enhancements [18]. The results are available in a tabular form in the website mentioned in ref. [18]. Figure 5 shows a comparison of the results of these calculations for ^{104}Pd with the enhanced NLD used in this work. Since the

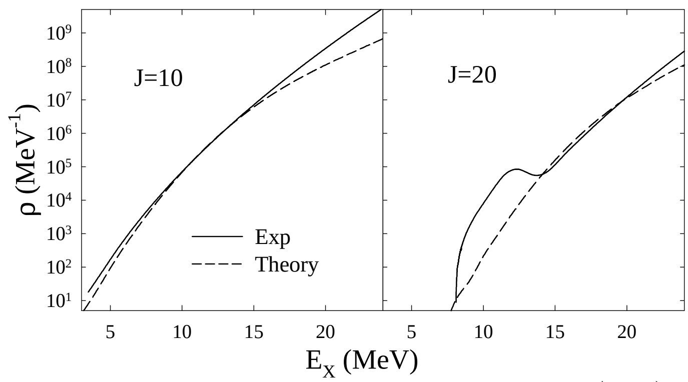

Figure 5. Experimentally extracted enhanced NLD (Exp.) and the calculated values (Theory) as a function of E_X for two angular momenta in ^{104}Pd.

absolute value of the NLD cannot be extracted from the measurements of particle spectra, the NLD values derived in the present work has been normalized to the calculation at $E_X = 10$ MeV and $J = 10$. The calculations, however, do not agree with the experimental E_X and J dependence of NLD. Our understanding of the NLD, not very far away from the yrast line, seems to be still inadequate.

The discrepancy between the measured and calculated fold-gated α-spectra, even after including the enhanced NLD prescription, points towards other non-statistical processes contributing to the spectra. As mentioned above, we have seen the discrepancy even for the inclusive spectra in the ^{12}C + ^{93}Nb reaction at low bombarding energies. The observed 'evaporation bump' showed up at a lower energy than that expected from the evaporation process. The discrepancies were not seen in ^{16}O-induced reactions [19] even at low bombarding energies. One reason for these observations could be the α-transfer reaction with the ^{12}C projectile. In this process, the ejectile ^{8}Be is unstable and breaks up into two α-particles. One of these two could reach the detector and add to the measured spectra. The spectrum from this process can peak at a lower energy (shifting with beam energy) compared to the evaporation bump position. Note that with the ^{16}O projectile, the α-transfer process creates the ^{12}C ejectile which is particle stable in its ground and the first excited states. If ^{8}Be is produced in an excited state, the energy of the α-particles from its subsequent decay has a wide distribution. This could mimic the appearance of a broad structure at α-energies well above the evaporation bump. Over and above, the massive transfer of ^{8}Be to the target could be possible even for low J in the final nucleus. All these issues indicate that the extraction of the NLD information from α-spectra in ^{12}C-induced reactions is difficult.

5. Summary and outlook

In summary, this paper describes an ongoing experimental program on the measurement of proton and article spectra in low-energy heavy-ion reactions at the Mumbai Pelletron Centre. The primary aim is to measure the excitation energy and angular momentum dependence of the nuclear level density. In the γ-multiplicity gated proton and α-spectra, measured with ^{12}C and ^{16}O beams on ^{93}Nb and ^{89}Y targets, an unusual feature of a broad structure at high particle energies is observed. In the case of proton spectra, the measurements establish the compound nuclear origin of the structures. A statistical model calculation with the conventional level density prescription fails to explain the data whereas an excitation energy and angular momentum-dependent enhancement in the level density appears to be successful. The enhancement probably corresponds to the collective enhancement in a certain regime of energy and angular momentum. A comparison of a recent microscopic calculation with the proposed level density, however, shows a disagreement. The broad structures also appear in the α-spectra. In this case, a statistical model calculation even with the enhanced level density cannot describe the data. Other reaction mechanisms like the α-transfer to the target followed by the break-up of the ^{8}Be ejectile as well as the ^{8}Be transfer to the target could be important.

In future, the present observations should be pursued in other systems, although, as mentioned in the Introduction, such a program of addressing the nuclear level density in a specific nucleus cannot be widely extended. The scope of the studies can be expanded with radioactive ion beams. In the case of α-spectra, measurements should be made with ^{16}O and other projectiles covering a wide angular range to shed more light on the possible non-statistical reaction mechanisms.

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