PRAMANA
— journal of
physics

© Indian Academy of Sciences

Vol. 67, No. 2
August 2006
pp. 369–374

Proton and alpha evaporation spectra in low energy ^{12}C and ^{16}O induced reactions

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MS received 20 September 2005; revised 24 March 2006; accepted 16 May 2006

Abstract. Proton and alpha particle spectra have been measured in the ^{12}C+^{93}Nb and ^{12}C+^{58}Ni reactions at $E(^{12}\mathrm{C}) = 40$ and 50 MeV and in the ^{16}O+^{93}Nb reaction at $E(^{16}\mathrm{O}) = 75$ MeV. The spectra are compared with the statistical model calculations. The shapes of the calculated spectra are in agreement with experimental data except for the alpha spectrum in the ^{12}C+^{93}Nb reaction at 40 MeV. The observed evaporation bump is at ∼2 MeV lower energy compared to the calculated one. This discrepancy could imply alpha particle emission from a deformed configuration before compound nucleus formation at this near Coulomb barrier beam energy.

Keywords. Evaporation spectra; statistical model; evaporation bump; fusion reaction.

PACS Nos 24.60.Dr; 25.60.Pj; 23.50+z; 23.60+e

1. Introduction

There are several measurements of charged particle spectra from the compound nuclei formed at different excitation energies and angular momenta in the fusion reactions. The statistical model (SM) has been used to understand these evaporation spectra [1]. In this model, the shape of the spectrum is determined mainly by the level density of the residual nucleus and the transmission coefficient for each emitted particle. The effective barrier (Coulomb and centrifugal) decides the shape of the low energy part of the evaporation spectrum including the evaporation bump. The sizes and shapes of the emitting nuclei influence the effective emission barriers and a measurement of these spectra, therefore, provides such information. Although the measured spectra are generally explained by the SM calculations [1], there are claims of significant discrepancies in some cases. For example, the measured alpha particle yields are seen to be enhanced in the sub barrier region, which lies below the evaporation bump, and the position of the bump is shifted down in energy compared to the SM predictions [2,3]. The SM calculations make use of the transmission coefficients obtained from the inverse absorption process of the particle by a nucleus in the ground state. The observed sub barrier enhancement may indicate a different Coulomb barrier for the evaporation and absorption processes. Most of the discrepancies are reported at beam energies well above the fusion barrier of the target-projectile system. It will be interesting to address the issue at relatively lower beam energies for different systems. With this motivation, the present work describes measurements in the ^{12}C+^{93}Nb, ^{12}C+^{58}Ni and ^{16}O+^{93}Nb systems.

2. Experimental details

The experiment was performed at the BARC–TIFR 14UD Pelletron laboratory at Mumbai. The reactions studied were ^{12}C+^{93}Nb and ^{12}C+^{58}Ni, both at $E(^{12}\mathrm{C})=$ 40 and 50 MeV, and ^{16}O+^{93}Nb at $E(^{16}\mathrm{O}) = 75$ MeV. Measurements were made in a one-meter diameter scattering chamber. The beam was collimated by a pair of tantalum collimators of diameter 2 mm and 3 mm kept at the distances of 50 cm and 150 cm, respectively, from the target. The targets were rolled metal foils of ^{93}Nb and ^{58}Ni (99.9% enriched), having thicknesses of 0.5 mg/cm^2 and 0.3 mg/cm^2, respectively. Protons and alpha particles were detected using two silicon surface-barrier ΔE–E telescopes with thickness combinations of (47 μm–2 mm) and (30 μm–2 mm). These were placed at the distances of 10.5 cm and 8.0 cm, subtending solid angles of 9.1 msr and 15.8 msr, respectively. Measurements were made at backward angles of 120° and 140°. Data were recorded as two-dimensional ΔE–E spectra in a CAMAC based multi-parameter data acquisition system.

The energy calibration was done using the alpha groups ($25 \leq E_\alpha \leq 40$ MeV) from the reaction ^{12}C(^{12}C,α)^{20}Ne* and the recoil protons (from the hydrocarbon compounds in the target) at a beam energy of 40 MeV by placing the detectors at 0°. A thin off-centred carbon target of thickness 20 μg/cm^2, backed by a 45 mg/cm^2 tantalum foil for stopping the beam, was used for this purpose. The target was kept at a distance of about 40 cm from the detectors to minimise kinematic broadening. The thickness of the tantalum foil was measured by weighing. The energy loss of protons and alpha particles through the tantalum backing was calculated using the stopping power compilation of Anderson and Ziegler [4]. The radioactive ^{241}Am+^{239}Pu and ^{229}Th alpha sources were used for calibrating the detectors at around 5 and 8 MeV. The stability of energy calibration was monitored by using a precision pulser during the runs. The gain variation in each detector was found to be less than 0.2%. The proton and alpha energy spectra were projected out from the two-dimensional ΔE–E spectra after putting appropriate gates.

The measurements were done at backward angles to minimise the spectral contamination from light impurities mainly due to the carbon build-up and the oxygen content in the target. The contributions from these two impurities were measured and found to be quite small for protons and negligible for alphas. The detailed procedure for background subtraction is given in ref. [5]. The background subtracted spectra at each laboratory angle were converted to those in the center of mass (c.m.) system. The ratio of the c.m. spectra at the two backward angles agreed with each other within 10% for proton and within 15% for alpha. Therefore these were averaged before comparing with the statistical model calculations.

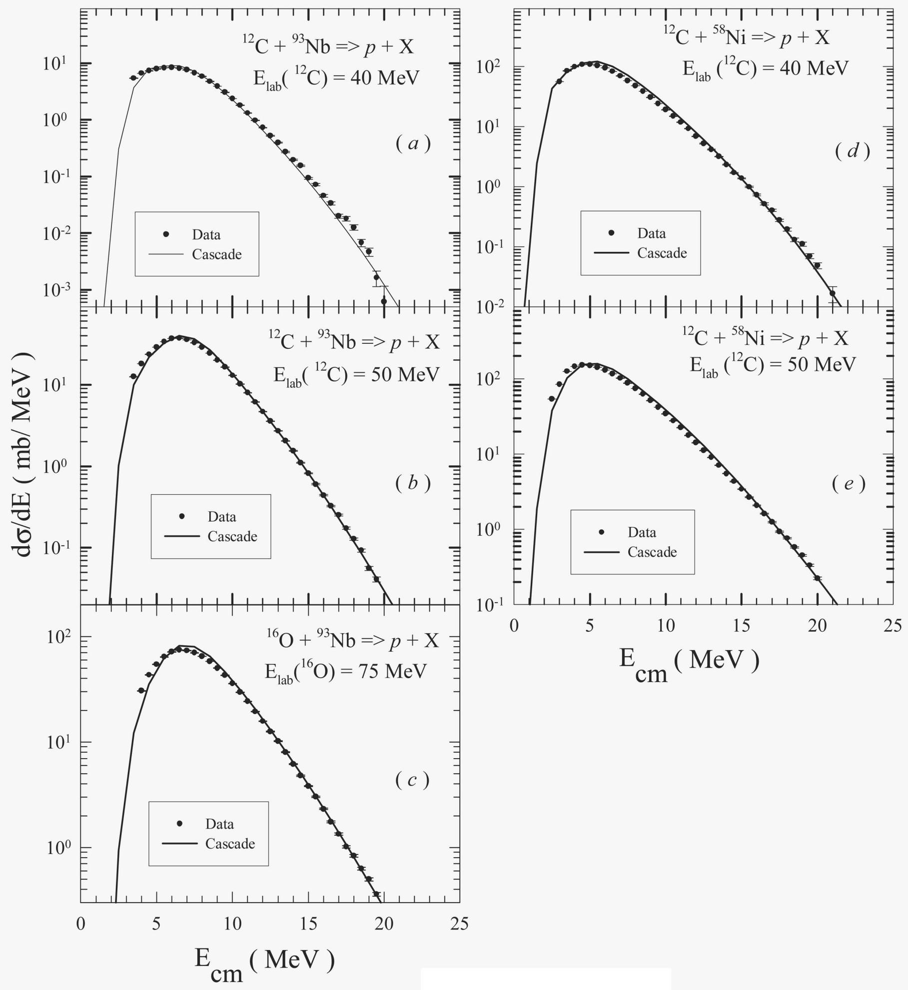

Figure 1. Proton spectra measured in various reactions along with the results of CASCADE calculations.

3. Results and discussion

The angle averaged energy spectra are shown in figures 1 and 2 for different systems studied. The statistical model spectra, calculated using the computer code CASCADE [6], are also shown. The important ingredients in the calculations are the transmission coefficients of the emitted particles and level densities of the residual nuclei. The transmission coefficients are calculated by using the corresponding optical model potentials (OMP). In this work the OMP parameters for n, p and α are taken from refs [7–10]. In all these calculations the level density prescription of Ignatyuk *et al* [11] is used with the asymptotic level density parameter of $\tilde{a} = A/8.5$, where A is the mass number of the nucleus.

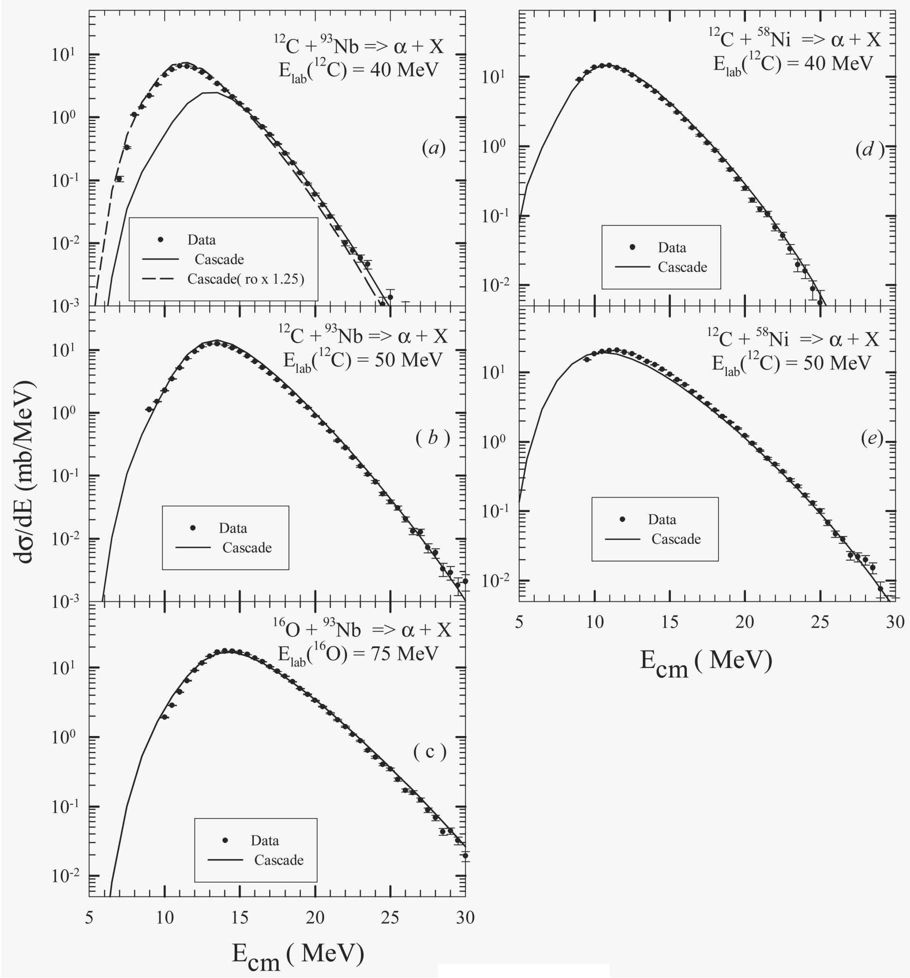

Figure 2. Alpha spectra measured in various reactions along with the results of CASCADE calculations. Figure 2a shows (dashed line) the calculations with r_0 increased by 25%.

From the comparison of the calculated spectra with the measured ones, it is clear that the shapes of the spectra agree well with the experiment for all cases, except for the alpha spectrum in the ^{12}C+^{93}Nb system at 40 MeV (figure 2a). In this case, there is a significant discrepancy between the data and the calculated spectrum in the evaporation bump region. The SM calculation underestimates the cross-sections below the bump by an order of magnitude and the experimental bump position is ~2 MeV lower in energy. In principle, a change in the level density parameter $\tilde{a}$ and the fusion cross-section, should change the position of the evaporation bump. When the level density parameter $\tilde{a}$ was varied from $A/7.5$ to $A/9.5$ the position of the bump was changed by ~0.2 MeV while the variation of the fusion cross-section by a factor of 2 changed the bump position by less than 0.1 MeV. The observed discrepancy for this case implies a reduction in the effective emission barrier for the alpha particle. This can be demonstrated by a CASCADE calculation using the transmission coefficients derived after artificially increasing the radius parameter r_0 (=r_C, the Coulomb radius parameter) from its original value of 1.17 fm. An increased r_0 mimics a reduction in the effective barrier. The dashed curve in figure 2a shows such a calculation with r_0 increased by 25%. The overall shape of the alpha spectrum is well reproduced. It may be argued that a change of radius parameter may be supported within the uncertainties of the OMP parameters in the literature. However, in that case a similar lowering of the evaporation peak should have been seen at higher beam energies also. The OMP parameters between alpha and the residual nucleus should not depend on the entrance channel energies of the ^{12}C+^{93}Nb system.

In the experiments at higher beam energies, the observed lowering of the effective emission barrier has been conjectured [3] as due to the evaporation from angular momentum-driven deformed configurations, formed dynamically during fusion, or due to thermal shape fluctuations. In the present case of the ^{12}C+^{93}Nb system at 40 MeV, the beam energy, due to its proximity to the Coulomb barrier, is not enough to populate high angular momenta. The above-mentioned effects are, therefore, not expected to be prominent. On the other hand, in the fusion of heavy ions the dynamics of the entrance channel can lead to a distribution of Coulomb barriers [12,13], which plays an important role in the near-barrier fusion processes. It is possible that the compound nucleus can be formed by fusion through the lower barrier with a prolate deformation in the initial target-projectile complex. If this shape survives sufficiently long for alpha particles to be emitted, it should lead to the enhanced alpha particle emission with the evaporation bump shifting to lower energy. Such a scenario might be supported by the fact that ^{12}C ground state wave function has a significant component of the highly deformed 3-α cluster state [14] at 7.65 MeV, which could be excited in the intermediate stages before the complete fusion. The above speculation about the possible origin of the observed discrepancy, however, has to be supplemented by two more speculations. The first one has to do with the observed agreement in the case of proton spectrum. This would imply that the proton emission takes place mostly after the full equilibration. If the deformed α-cluster configuration plays an important role in the creation of the deformed shape, then the alpha emission could be more dominant in the stages prior to the full equilibration. The second point is regarding the observed agreement at the beam energy of 50 MeV. This would imply that the formation of the deformed shapes is less important at higher beam energies for changing the alpha spectrum. This, in turn, would mean that at higher beam energies, the shape does not survive long enough for alpha emission to take place. It may be mentioned, however, that a dynamical trajectory calculation using the code HICOL [15] does not show any significant difference in the equilibration time at the two beam energies and, hence, does not support the above speculations.

More systematic measurements are necessary to clarify the issue. For example, it will be interesting to see whether such discrepancy is there in other ^{12}C induced reactions near the barrier and if it is less for other projectiles.

4. Summary

Proton and alpha particle spectra have been measured at backward angles in reactions ^{12}C+^{93}Nb and ^{12}C+^{58}Ni at $E(^{12}\mathrm{C}) = 40$ and 50 MeV and in ^{16}O+^{93}Nb at $E(^{16}\mathrm{O}) = 75$ MeV. The spectra are compared with the statistical model calculations. The calculated spectra are in agreement with experimental data for all the systems except for the alpha spectrum in the ^{12}C+^{93}Nb reaction at 40 MeV. The calculation underestimates the cross-sections below the evaporation bump and the bump is observed at a lower ($\sim$2 MeV) alpha energy. In this case the beam energy is near the fusion barrier of the target-projectile system. It is speculated that in the entrance channel at energies near the barrier the fused system can be formed with a prolate deformation due to the initial distortion in the target-projectile complex. If the alpha particles are emitted during the shape equilibration process it could resolve the observed discrepancy. The agreement for the proton spectra would imply that the proton emission takes place after the full equilibration. The role played by the excited α-cluster configuration in ^{12}C prior to complete fusion could be responsible for these observations. The observed agreement at 50 MeV would imply a faster equilibration time at higher beam energies.

Acknowledgement

The authors would like to thank the Pelletron accelerator staff for the smooth operation of the machine.

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