Measurement of Nuclear Temperature from Different Fragment Spectra

A. De[1], A. Ray[2*], S. R. Banerjee[2], S. Kailas[3], and A. Chatterjee[3]
[1]Raniganj Girls' College, Raniganj, PIN-713358, INDIA
[2]Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata – 700064, INDIA
[3]Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai-400085, INDIA
* email: ray@veccal.ernet.in

Introduction

The temperature of a daughter nucleus can be determined from the corresponding charged particle evaporation spectrum of the parent nucleus. Usually the proton and alpha particle spectra from the excited compound nuclei are used to determine [1, 2] the temperatures of the corresponding daughter nuclei. Let us consider the statistical evaporation decay of an excited compound nucleus (with excitation energy E_X). Let E_k^{rot} be the rotational kinetic energy of an emitted fragment of type k and T_k be the temperature of the daughter nucleus produced as a result of the emission of the k-type fragment, then $E_X - E_k^{rot} = \left(\frac{A}{\alpha}\right) T_k{}^2$, where A is the mass number of the daughter nucleus and α denotes the level density parameter. In the case of emission of heavier fragments, E_k^{rot} would increase significantly compared to the rotational kinetic energy associated with the alpha or proton emission, because much higher orbital angular momenta are involved for the heavier fragments and so the available thermal energy of the excited compound nucleus would also decrease considerably. However the corresponding mass number (A) of the daughter nucleus would also decrease. It turns out that for the light charged particle emissions such as proton and alpha emissions from a relatively massive compound nucleus, the temperatures of the daughter nuclei would be about the same, as observed experimentally [2]. However for the emission of heavier fragments, the increase of E_k^{rot} would be much more than the decrease of the mass number (A) of the daughter nucleus, because E_k^{rot} increases as the square of the orbital angular momentum of the emitted fragment and the corresponding temperature (T_k) of the daughter nucleus should decrease considerably. It is interesting to study experimentally the variation of the temperatures of different daughter nuclei produced as a result of the emission of different types of fragments from an excited compound nucleus.

Experiment

The back-angle fragment spectra from alpha to oxygen were measured [1, 3] from ^{16}O+^{89}Y, ^{12}C+^{93}Nb and ^{16}O+^{93}Nb reactions at $E_{c.m}$=81.3 MeV, 75.7 MeV and 99 MeV respectively. The back-angle angular distributions of different fragments from alpha to oxygen were found [1, 3] to be approximately following $1/\sin\theta_{c.m}$ function implying long lifetime ($> 5 \times 10^{-21}$ s) of the intermediate complex. The comparison of the yields of oxygen nuclei from ^{16}O+^{89}Y and ^{12}C+^{93}Nb forming the same intermediate complex at the same excitation energy and very similar spin distribution shows a strong entrance channel dependence [3] implying orbiting for the emission of the oxygen nuclei. However for the emission of alpha, lithium, boron, beryllium and carbon nuclei, no such entrance channel dependence was observed [3], implying their statistical compound nuclear origin. The temperatures of the daughter nuclei and the Coulomb barrier of the daughter and the emitted fragment nuclei have been determined by fitting the corresponding angle-integrated spectrum (assuming $1/\sin\theta_{c.m}$ angular distribution) with Moretto's algebraic formula [4] for the statistical emission of particles as given below.

$$P(x) \propto \exp(-x/T)\,erfc\left(\frac{p-2x}{2\sqrt{pT}}\right) \text{...........(1)}$$

Where x=E_{kin}(c.m)-V_C. Here V_C, E_{kin}(c.m), p, T are the Coulomb barrier energy between the daughter and the emitted fragment nuclei, exit channel center of mass kinetic energy, amplification factor and the temperature of the daughter nucleus respectively. Amplification factor (p) and Coulomb barrier (V_C) characterize the emitted fragment and their values increase for heavier fragments. The spectra of alpha, lithium, boron, beryllium and carbon have been fitted reasonably well with one source fit using eq (1). The evidence for the sequential decay of alpha particles was found [1] from an analysis of very high statistics alpha spectra. However there is no evidence of sequential decay for the emission of the heavier fragments. In Table 1, we show the temperatures (T) of the daughter nuclei and the corresponding Coulomb barrier (V_C) obtained by fitting different fragment spectra from ^{16}O+^{89}Y at $E_{c.m}$ = 81.3 MeV. It was found that contrary to the expectation of the lower temperatures of the daughter nuclei, the extracted temperatures of Rh, Mo and Nb produced as a result of the emission of alpha, boron and carbon nuclei from the parent Ag are about the same (≈3 MeV). The temperature of Ru produced as a result of the emission of lithium nuclei has been found to be somewhat higher. However the entrance channel oxygen spectrum from ^{16}O+^{89}Y reaction, required a 2-source fit—a dominant source (identified as an orbiting source) at a significantly lower temperature of T= 1.5 MeV and a much weaker source (identified as a compound nuclear source) at T=3.1 MeV. Considering the increase of the rotational kinetic energy (E_k^{rot}) for oxygen emission in comparison to alpha emission, we find that the temperature of yttrium nucleus produced as a result of the oxygen emission should be about 1.6 MeV, in reasonable agreement with the temperature (T=1.5 MeV) extracted from the corresponding orbiting component of the oxygen spectra. However the temperature extracted from the compound nuclear component of the oxygen spectrum is much higher (3.1 MeV) and in agreement with the higher temperature obtained from other fragments. Similar results have been obtained from the analysis of the evaporation fragments from ^{12}C+^{93}Nb and ^{16}O+^{93}Nb reactions also. We obtained about the same temperature (≈ 3 MeV) by analyzing alpha, boron, beryllium and carbon spectra coming from the ^{12}C+^{93}Nb reaction at $E_{c.m.}$ = 75.7 MeV. No orbiting effect was seen [3] for the ^{12}C+^{93}Nb reaction. ^{16}O+^{93}Nb reaction shows [3] orbiting effect only in oxygen channel and the extracted temperatures show similar pattern as found for ^{16}O+^{89}Y reaction.

So it has been found that the temperatures extracted from the spectra of the heavier evaporation fragments are about the same as obtained from the alpha spectra, although a simple analysis would predict considerable lower temperature of the daughters produced as a result of the emission of heavier fragments carrying much higher rotational energy. These results may suggest the effect of lifetime on the nuclear temperature.

Table 1: Temperatures of daughter nuclei

Reaction	Temperature of daughter nucleus (MeV)	Coulomb barrier (MeV)
^{89}Y(^{16}O,^{4}He)Rh	(2.9 ± 0.1)	11.9 ± 0.1
^{89}Y(^{16}O,Li)Ru	(4.5 ± 0.5)	19.2 ± 0.4
^{89}Y(^{16}O,B)Mo	(3.3 ± 0.3)	29 ± 1
^{89}Y(^{16}O,C)Nb	(3.0 ± 0.1)	34.6 ± 0.3
^{89}Y(^{16}O,O)Y (CN)	(3.1 ± 0.2)	42.85 ± 1
^{89}Y(^{16}O,O)Y (Orbiting)	(1.5 ±0.1)	38 ± 0.2

References

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