Temperature from fragment spectra and possible lifetime effect

A. De[1]* and A. Ray[2]
[1]*Raniganj Girls' College, Raniganj, West Bengal, INDIA*
[2]*Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata – 700054, INDIA*
* *email:aks.panua@gmail.com*

Introduction

The temperature of a system is defined when it is in full statistical equilibrium which means that each possible state of the system is populated with equal probability. If E be the energy of the system and it comprises a fixed N number of particles, then $\frac{1}{T} = \frac{\partial S(E,N)}{\partial E}$, where T is the temperature of the system, S is the entropy of the system and ρ the density of states of the system at energy E. The atomic nucleus is a microscopic system and the temperature of a nucleus is defined when its excitation energy is much greater than the first excited state energy. Since no external probe can be used, so the information about the temperature of a nucleus has to be obtained from the emission of the small parts of the nucleus itself. The necessary conditions are that the emission process must be completely statistical and the emitted particles must be part of the equilibrium and the density of states of the whole system before emission. The statistical emission of particles usually takes place from a compound nucleus and the spectrum of the emitted particles shows an exponential tailing. The slope of the exponential tail of the statistical particle spectrum gives the temperature of the residual nucleus produced in the exit channel at the instant of the emission of the particle from the exit channel dinuclear system (residual + emitted particle). The residual nuclei are produced with a distribution of the excitation energy and the slope of the statistical particle spectrum gives the temperature of the ensemble of the residual nuclei corresponding to their average excitation energy.

Following Moretto [1], the statistical evaporation spectrum of charged particles from a compound nucleus can be written as

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

$$x = E_{kin}(c.m.) - V_C.$$

Here V_C is the Coulomb barrier, p is the amplification parameter of the system and T is the temperature of the residual nucleus. The temperature T of the residual nucleus can be obtained by fitting the statistical evaporation spectrum with eq(1). Usually the temperature is obtained by fitting evaporation proton and alpha spectra from a compound nucleus. The effect of the sequential decay is considered by adding up several source terms with decreasing temperatures.

$$P \propto \left(\sum_i exp\left(-\frac{x_i}{T_i}\right) erfc\left(\frac{p_i - 2x_i}{2\sqrt{p_i T_i}}\right) \right)$$

Where $x_i = E_{kin}(c.m.) - (V_C)_i$

$(V_C)_i$, p_i, T_i, denote the Coulomb barrier, amplification parameter and residual temperature of the i^{th} source.

Although generally the temperature is determined from the slopes of the evaporation proton and alpha spectra, the temperatures of the corresponding residual nuclei can also be obtained by fitting heavier fragment (such as Li, Be, B ,C) evaporation spectra with eq(1), provided those emissions are also completely statistical. The temperatures of the residual nuclei obtained by fitting heavier fragment evaporation spectra should be significantly lower compared to those obtained from proton or alpha spectra, because the heavier fragment such as Li, Be, B or C takes away significantly more orbital kinetic energy, thus lowering the available thermal energy.

$$U_{Thermal}(residual) = (E_{c.m.} - Q) - \frac{\ell(\ell+1)\hbar^2}{2I} - E_{rot}(spin)$$

Where $E_{c.m.}$, Q, E_{rot}(spin) are the center of mass energy, Q-value of the reaction and spin rotational energy of the nuclei respectively. I and ℓ denote the moment of inertia and the orbital

angular momentum of the system respectively. In the case of heavy fragment emission, generally $E_{rot}(spin) \ll \frac{\ell(\ell+1)\hbar^2}{2I}$ and the orbital rotational energy shows up as the kinetic energy in the exit channel.

It has been observed [2,3] from our study of the back-angle fragment emissions (α, Li, Be, B, C) from the $^{16}O+^{89}Y$ and $^{12}C+^{93}Nb$ reactions at $E_{c.m}$= 81.4 MeV and 75.7 MeV respectively as well as from the study of the $^{35}Cl+^{24}Mg$ reaction at $E_{c.m}$= 105.7 MeV that the temperatures obtained from the alpha spectra agree with the statistical model calculations, but the temperatures obtained by fitting the fragment spectra with eq.(1) do not show the expected trend of decreasing temperature with the emission of the heavier fragment as the later takes away more kinetic energy, thus reducing the thermal energy. According to statistical model calculations, the temperatures obtained from the alpha, Li, B and C spectra from 16O+89Y reaction at Ec.m =81.4 MeV should be 3 MeV, 2.35 MeV, 2.1 MeV and 1.7 MeV respectively, but according to the experimental observations, the temperatures are 2.9 MeV, 4.2 MeV, 3.3 MeV and 3.5 MeV respectively, thus showing no trend of decrease for the heavier fragments.

We conjecture that our observations might imply the effect of the life-time of the exit channel dinuclear system (residual and ejectile system) on the measured temperature of the residual nucleus at the instant of its separation from the dinuclear system. The lifetime of the exit channel dinuclear system is inversely proportional to the transmission coefficient of the ejectile. Since the average transmission coefficient of ^{12}C (emitted with a mean kinetic energy of 34 MeV and ℓ=40$\hbar$) is much larger than that of ^{4}He (emitted with a mean kinetic energy of 15 MeV and ℓ=11-12$\hbar$), so the average lifetime of $^{12}C+^{93}Nb$ dinuclear system should be much shorter than that of $^{4}He+^{101}Ru$ dinuclear system. In the statistical model calculation, the lifetime of the exit channel dinuclear system has been implicitly assumed to be infinitely long and so although the fragment and the residual nucleus separate out after a short time, the slope of the exponential tail of the fragment spectrum remains unaffected by the lifetime of the dinuclear system. Considering the quantum uncertainty principle, the slope of the fragment spectrum indicating the measured temperature of the ensemble of the residual nuclei might be affected by the short lifetime of the dinuclear system. If we consider an average width of the exit channel dinuclear states, then the exponential tail of the fragment spectrum might extend to higher energy implying a higher temperature for the corresponding residual nucleus at the time of separation from the exit channel dinuclear system. On the other hand, we observed $1/\sin\theta_{c.m.}$ angular distribution of the fragment (such as ^{12}C) at back angles in the center of mass frame implying a long lifetime of the exit channel dinuclear complex and contradicting the earlier conjecture of the short lifetime. However one should also get a $1/\sin\theta_{c.m.}$ angular distribution in the case of the emission of the fragments in a plane perpendicular to the direction of the orbital angular momentum. Alternatively, if the initial decay of the heavy fragment and residual system (such as $^{12}C+^{93}Nb$) is assumed to be non-exponential [4,5], then also a relatively longer lifetime resulting in the observed $1/\sin\theta_{c.m.}$ angular distribution might be possible, even though the later exponential decay responsible for the width of the dinuclear state might be fast.

References

[1] L. G. Moretto et al., J. Phys. G **23**, 1323 (1997).
[2] A. De et al., International Symp. On Nucl.Phys. **v54**, 406 (2009).
[3] D. Mahbou, PhD thesis Universite Louis Pasteur, Strasbourg, France (1996).
[4] L. Fonda, G. C. Ghirardi and A. Rimini Rep. Prog. Phys. **41** 587 (1978).
[5] A. Sudbery, Annals of Physics **157** 512 (1984).