Consistency of nuclear thermometric measurements at moderate excitation

T. K. Rana,* C. Bhattacharya, S. Kundu, K. Banerjee, S. Bhattacharya, A. Dey,† T. K. Ghosh, G. Mukherjee, J. K. Meena, D. Gupta,‡ S. Mukhopadhyay, D. Pandit, S. R. Banerjee, A. Roy, and P. Dhara
Variable Energy Cyclotron Centre, 1/AF, Bidhan Nagar, Kolkata 700 064, India
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A comparison of various thermometric techniques used for the estimation of nuclear temperature has been made from the decay of hot composite $^{32}S^*$ produced in the reaction ^{20}Ne (145 MeV) + ^{12}C. It is shown that the temperatures estimated by different techniques, known to vary significantly in the Fermi energy domain, are consistent with each other within experimental limits for the system studied here.

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An unambiguous estimation of the thermodynamic properties (temperature, density, specific heat, etc.) of excited nuclear systems, formed in low and intermediate energy heavy ion collision, is a longstanding problem. The estimation of the thermodynamic variables in general, and temperature in particular, of a hot nucleus formed in energetic nucleus-nucleus collision is crucial to characterize the equation of state of finite nuclear matter and to identify the possible phase transition in such a system [1,2]. Experimentally, to study the nuclear thermodynamics one needs to associate the detected reaction products with the thermodynamical variables of the decaying source, i.e., temperature, density, etc. (one needs a correct models of the temperature-dependent partition function to reconstruct the deexcitation chain) [3,4]. At low excitation energy (<1 MeV/nucleon), this is accomplished by the theory of a compound nucleus. At higher excitation energies, the opening of various reaction channels (e.g., incomplete fusion, multifragmentation) leads to an additional complication in establishing a direct relationship between the theoretical models and the experimental observations and, thereby, makes the job of proper evaluation of temperature increasingly difficult.

Experimentally, several schemes have been proposed and employed in recent years to estimate the 'temperature' of the hot nucleus, e.g., slope thermometry [5–9], excited-state thermometry [10–13], double-isotope thermometry [14–16]. All of these are based on the assumption of thermal equilibrium and are thus apparently equivalent. It is, however, curious to note that the quantitative results of different thermometric measurements are often not mutually consistent in the Fermi-energy domain [17–21]. As the 'temperature' is a time-dependent variable, different thermometers may be efficient in probing different stages of the temporal evaluation of the reaction process, thus making the comparison between different 'thermometers' difficult at higher excitation energy. Alternatively, as new reaction processes are switched on with an increase in collision energy, dynamical effects (e.g., relaxation dynamics, Fermi motion) and sequential statistical emission become more and more significant, thus adding to the uncertainty in temperature measurement. It is, therefore, likely that the 'thermometers' mentioned above are affected by varying degrees by each of these processes leading to 'observed' inconsistency between various thermometers [17–21].

It is clear from the above that a systematic measurement of temperature using various thermometric techniques at moderate excitation energies (reactions well above the Coulomb barrier but well below the Fermi-energy domain, where incomplete fusion, nonfusion channels are switched on) would provide a clue about the origin of differences between various thermometric measurements in the Fermi-energy domain. Here we report a comparative study of nuclear thermometric techniques at moderate excitation energy ($E^* \sim 73$ MeV) for the well-studied reaction ^{20}Ne (145 MeV) + ^{12}C [22–24] and show that in the present case, all thermometric measurements are consistent within experimental uncertainties. The experiment was performed in a single run to minimize the contributions of systematic errors in the estimated temperatures.

The experiment has been performed at the Variable Energy Cyclotron Centre, Kolkata, India, using 145 MeV ^{20}Ne beam on a ^{12}C target (self-supported, thickness $\sim$550 μg/cm^2). Different fragments have been detected using a three-element telescope. The telescope consisted of a 65 μm ΔE single-sided silicon strip detector (SSSD), 300 μm $E/\Delta E$ double-sided silicon strip detector (DSSD) and backed by four CsI(Tl) crystals (thickness $\sim$4 cm). The 65 μm SSSD silicon wafer was segmented into 16 strips. The 300 μm DSSD wafer was segmented into 16 strips on its junction (front) side while the ohmic surface (rear) was segmented into 16 strips in the orthogonal direction (256 pixels in total). The detector telescope was placed at a distance 20 cm from the target. The angular range in the laboratory covered by the telescope was from 27° to 40°. Typical angular resolution of each strip is ±0.4°. All strips and the CsI(Tl) detectors were read out individually using standard readout electronics. A VME-based online data acquisition system was used for the collection of data on an event-by-event basis. The silicon detectors were calibrated using an elastically-scattered ^{20}Ne ion from a ^{197}Au target, a precision pulser and a ^{229}Th α-source. The

*tapan@veccal.ernet.in
†Present address: Saha Institute of Nuclear Physics, 1/AF, Bidhan Nagar, Kolkata-64, India.
‡Present address: Bose Institute, Department of Physics Centre for Astroparticle Physics and Space Science, EN Block, Sector V, Salt Lake City, Kolkata-91, India.

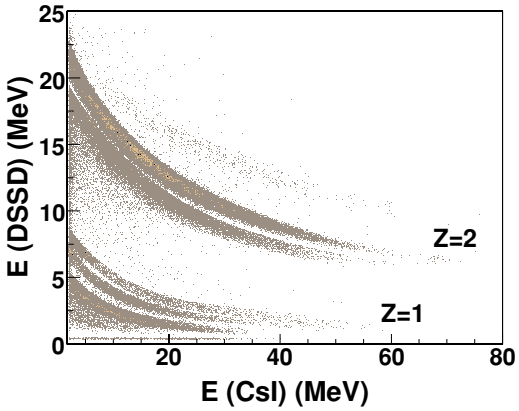

FIG. 1. (Color online) Typical two-dimensional ΔE-E scatter plot between the DSSD (E) and the CsI(Tl)(E) detectors.

energy calibration of the CsI(Tl) detectors was done using the two-dimensional spectra between the 300 μm Si-strip and the CsI(Tl) detectors [25]. The event reconstruction from the hit patterns in orthogonal directions of the DSSD provided two-dimensional position information of the detected particle. A typical two-dimensional spectrum obtained with the 300 μm Si (DSSD) and CsI(Tl) detectors is shown in Fig. 1. This shows clearly separated bands corresponding to isotopes of $Z = 1$ and $Z = 2$ particles. Extracted particle spectra were then used to estimate nuclear temperature using the different thermometric techniques described below.

Temperature from slope thermometry: This method is based on the concept of a canonical ensemble. The particles evaporated from the hot system are taken to be Maxwellian in shape [26] and the value of the temperature can be extracted from the slopes of the kinetic energy spectra of light charged particles [5–9]. Experimentally obtained proton and α-particle spectra in the center of mass are shown in Figs. 2 and 3, respectively.

In order to extract temperature using the slope thermometer, the spectra have been fitted with a function $\sim f(E_{\mathrm{c.m.}})exp(-E_{\mathrm{c.m.}}/T)$, shown by the solid line in Figs. 2 and 3. The temperatures extracted from the slopes of proton and α spectra are $T = 2.6 \pm 0.3$ MeV and $T = 2.9 \pm 0.5$ MeV, respectively.

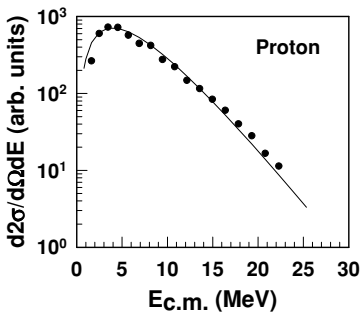

FIG. 2. Typical energy spectrum of protons in the c.m., for the reaction $^{20}\mathrm{Ne} + ^{12}\mathrm{C}$. Filled circles are the experimental data and the solid line represents the fitted curve to extract the slope.

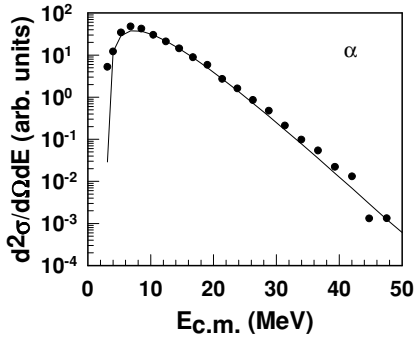

FIG. 3. Same as Fig. 2 for α particles.

Temperature from excited-state thermometry: This approach is meaningful if the emitting subsystem is not only close to kinetic equilibrium but also close to chemical equilibrium. By knowing the phase space of the decay configuration, the "emission temperature" can be determined from the relative abundances of different particle species, or more directly from the relative populations of states in a given nucleus [10–13]. The ratio, R_p, of the populations of two states (if no feeding by particle decay takes place) is related to the temperature (T) through the relation

$$R_p = \frac{(2j_u + 1)}{(2j_l + 1)} \exp(-E_{\mathrm{diff}}/T), \tag{1}$$

where j_u and j_l are the spins of the upper and lower states, respectively, and E_{diff} is the energy difference between these two states. In order to extract the information of the population of different particle-unstable states, we have measured the coincidence yield (sum of all coincident pair of hits between any two front side strips of DSSD) detected from the decay of particle-unstable nuclei and extracted the two-particle correlations function [27,28], as defined below.

The two particle angle-averaged correlation function, $1 + R(q)$, is defined experimentally by the following equation:

$$\sum Y_{12}(p_1, p_2) = C_{12}[1 + R(q)] \sum Y_1(p_1)Y_2(p_2), \tag{2}$$

where p_1, p_2 are the laboratory momenta of the coincident pair of particles with masses m_1 and m_2, q $(= \mu|(\frac{p_2}{m_2} - \frac{p_1}{m_1})|)$ is the relative momentum of the correlated pair, and C_{12} is a normalization constant which is determined by the requirement that $R(q) = 0$ for large q. The sum on both sides of Eq. (2) are taken over all detectors and particle energy combinations satisfying a specific gating condition. Y_1 and Y_2 are the single-particle yields for particle 1 and 2, respectively, and $Y_{12}(p_1, p_2)$ is the two-particle coincidence yield.

Experimentally, the product of single particle yields $Y_1(p_1)Y_2(p_2)$ has been approximated as 'uncorrelated' two particle yields, $Y_{12}^{\mathrm{unc}}(p_1, p_2)$, and was constructed by the 'event-mixing technique' [29]. The two-particle correlation functions have been calculated as

$$\sum Y_{12}(p_1, p_2) = C_{12}[1 + R(q)] \sum Y_{12}^{\mathrm{unc}}(p_1, p_2). \tag{3}$$

The α-α correlation function obtained in the reaction $^{20}\mathrm{Ne} + ^{12}\mathrm{C}$ is shown in Fig. 4. The background from the total

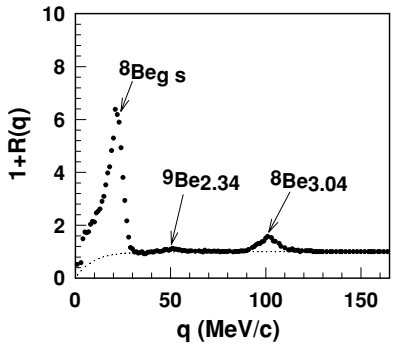

FIG. 4. α-α correlation functions plotted as a function of the relative momentum, q, for the reaction ^{20}Ne + ^{12}C at 145 MeV. Filled circles are the experimental data and the dotted line is the background (see text).

coincidence yield which do not proceed through the decay of particle-unstable nuclei is shown in dotted line in the Fig. 4 [30]. The peaks at $q = 20$ MeV/c and 100 MeV/c correspond to decays of the particle-unstable ground state of ^{8}Be ($J^\pi = 0^+$) with decay width of 6.8 eV and the 3.04 MeV excited state of ^{8}Be ($J^\pi = 2^+$) with decay width of 1.5 MeV, respectively. Both of these states decay only by α particle emission. In addition, the peak at $q = 50$ MeV/c is due to the decay of the 2.43 MeV state in ^{9}Be.

The d-α correlation function obtained in this experiment is shown in Fig. 5. The measured correlation function exhibits two maxima corresponding to the $J^\pi = 3^+$ unstable excited state of ^{6}Li at 2.186 MeV with decay width of 24 keV and the $J^\pi = 2^+$ at 4.31 MeV excited state of ^{6}Li with decay width 1.3 MeV, respectively. A third peak, corresponding to 5.65 MeV excited state of ^{6}Li with decay width of 1.9 MeV is also observed in the correlation function, which is in close proximity with the second peak.

Nuclear temperatures have been extracted both from ^{8}Be and ^{6}Li decays using the α-α correlation and d-α correlation spectra, respectively. The populations of the particle-unstable states were extracted by integrating the experimental yields over the range of q dominated by the corresponding resonance. The temperature has been extracted using Eq. (1) from the ratio of yields of $^8\mathrm{Be}_{\mathrm{g.s.}}/^8\mathrm{Be}_{3.04}$ and is found to be $T = 2.2 \pm 0.5$ MeV. Similarly, the temperature has been extracted from the ratio of yields of $^6\mathrm{Li}_{2.186}/^6\mathrm{Li}_{4.31}$ and is found to be $T = 2.6 \pm 0.4$ MeV.

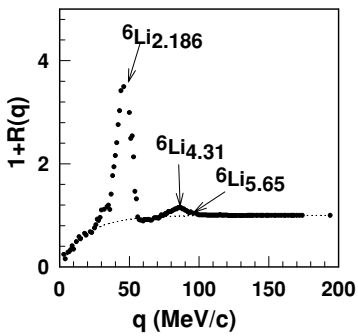

FIG. 5. Same as Fig. 4 for d-α pairs.

Temperature from double-isotope thermometry: This method evaluates the temperature of equilibrated nuclear regions from which light fragments are emitted using the yields of different light nuclide. In this scheme, originally proposed by Albergo *et al.* [31] based on the grand canonical ensemble, the isotope yield for a system in chemical and thermal equilibrium can be related to temperature T_{iso} via the expression

$$T_{\mathrm{iso}} = \frac{B}{\ln(aR)}, \tag{4}$$

where 'R' is the ground state fragment yield ratio, 'B' is the binding energy parameter, and 'a' is the statistical weights of the ground state nuclear spins. Expressions for B, a, and R are

$$B = BE(A_i, Z_i) - BE(A_i + \Delta A, Z_i + \Delta Z) - BE(A_j, Z_j) + BE(A_j + \Delta A, Z_j + \Delta Z), \tag{5}$$

$$a = \frac{[2S(A_j, Z_j) + 1]/[2S(A_j + \Delta A, Z_j + \Delta Z) + 1]}{[2S(A_i, Z_i) + 1]/[2S(A_i + \Delta A, Z_i + \Delta Z) + 1]} \times \left(\frac{[A_j/(A_j + \Delta A)]}{[A_i/(A_i + \Delta A)]}\right)^{\gamma}, \tag{6}$$

$$R = \frac{[Y(A_i, Z_i)/Y(A_i + \Delta A, Z_i + \Delta Z)]}{[Y(A_j, Z_j)/Y(A_j + \Delta A, Z_j + \Delta Z)]}. \tag{7}$$

Here, $BE(A_i, Z_i)$, $S(A_i, Z_i)$, and $Y(A_i, Z_i)$ are the known binding energy, ground-state spin, and the total yield of the fragment with mass A_i and charge Z_i, respectively. The value of ΔA and ΔZ are chosen to be same for both ith and jth fragment pairs [31]. The value of the exponent γ is 1 or 1.5 depending on the assumption of surface or volume emission, respectively. In order to remove the Coulomb effects in determining the temperature using double-isotope thermometer, we have taken system with $\Delta Z = 0$ and $\Delta A = 1$, which is the most reliable thermometer [14]. The temperature has been calculated, assuming γ to be 1 (surface emission), using Eq. (4) from the isotopic yields of p, d, t, ^{3}He, and α. The temperature of hot composite ^{32}S* was estimated to be 2.6±0.2 MeV from the double isotopic yields of (p, d), (^{3}He, α), and 2.4 ± 0.3 MeV from the yields of (d, t), (^{3}He, α), respectively.

Thus, temperatures of excited composite ^{32}S* formed in the nuclear reaction ^{20}Ne + ^{12}C have been estimated using different thermometric techniques. The experiment was performed in a single run to minimize the contributions of systematic errors. The estimated temperatures are shown in Fig. 6 and

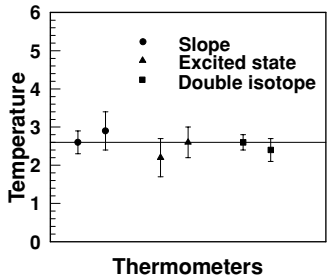

FIG. 6. Comparison of temperatures obtained from different "thermometers." The solid line is the weighted average.

their weighted average value (2.6 ± 0.1) is shown by solid line. From Fig. 6 it is evident that temperatures estimated by different techniques are consistent within the limits of experimental uncertainties for the present system, which is contrary to the observations at higher excitation energies (reactions in the Fermi-energy domain). Similar systematic measurements (where all thermometric measurements are done simultaneously) at higher energies may throw more light on the evolution of the discrepancy *vis a vis* the related reaction scenario.

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