High Energy Physics and Nuclear Physics

Volume 21, Number 3

Influence of IMF Internal Excitation on the Extraction of the Isotope Nuclear Temperature

Wei Zhiyong and Zhu Yongtai

(Institute of Modern Physics, The Chinese Academy of Sciences, Lanzhou, China)

The single-particle level densities, calculated under the local density approximation and based on the Fermi gas model, are used to obtain the partition functions. The results show that the internal excitation of the intermediate mass fragments (IMF) decayed from a hot nucleus have strong effect upon the extraction of the isotope nuclear temperature.

Key words: isotope nuclear temperature, IMF, partition functions.

1. INTRODUCTION

With the further development of the research on intermediate energy heavy ion reactions, the study on the multifragmentation [1-3] related to the characteristics of hot nuclei [1,2], the equation of state of nuclear matter, and the compressibility, thermalization, and decay of nuclear matter [3-5] have captured worldwide interest. The statistical model method has been used in the study on the nuclear collective characters [6-8]. The temperature is one of the important parameters in different statistical model treatments. Moreover, some pioneering research works, e.g., the study of the nuclear liquid-gas phase transition, are also closely related to the measurement of nuclear temperature [9-11].

For a long time, there were different opinions about the nuclear temperature and the principle and method of its measurement. There are still mainly two questions: (1) Is an equilibrium or partial

Received on June 18, 1996. Supported by the National Natural Science Foundation of China.

equilibrium reached in the nuclear reaction? This question is important because only in the case of equilibrium is the term of "temperature" meaningful. (2) The emitted particles and fragments, measured in the nuclear reactions, are the successive decay products of the primary reaction products. They can be emitted at different stages of the compression and expansion of the nuclear matter. The temperature could be different at different stages of nuclear reaction process. Generally, the temperature of the system refers to the temperature when the particles are emitted after the thermalization of the system. How can the information be obtained at the stage of freeze-out from the measured value? One still has to do some additional work [9-11]. These two problems are closely connected with the dynamic process of the nuclear reaction. According to the thermodynamic and statistical definition of the temperature, nuclear temperature should be: $1/T(E) = \partial[\ln\Omega(E)]/\partial E$. In fact, one cannot get the exact number of states $\Omega(E)$ for a nuclear system. Therefore, it is impossible to obtain an exact temperature. One can only find an approximate method to extract the nuclear temperature from some physical observable directly measured in the reaction process.

In recent years one of the methods widely used to extract the nuclear temperature is to measure the correlation function of the light-charged particles emitted in the nuclear reaction, and from the relative population of uns particles to extract the population nuclear temperature [12-14]. For two well-separated and isolated energy levels with spin S_i and decay channel branch ratio Γ_i, geometrical efficiency of the detector ε_i, when the resonance is assumed to be sharp enough, the relative yield is: $R = \varepsilon_2(S_2 + 1)\Gamma_2/[\varepsilon_1(S_1 + 1)\Gamma_1]\exp[-(E_2 - E_1)/T]$. Using the light-charged particle correlation measurement method, the relative population between the excited state and ground state or between two excited states of the light nuclei such as ^{4}He, ^{5}Li, ^{6}Li, ^{7}Li, and ^{8}Be can be determined quite well. It is assumed in the statistical model that the relative population of the intrinsic excitation of the first emitted IMF should be the same as that of the primary emitter. In the process of successive emissions the temperature of the emitter, the kinetic energy of the emitted particles, and the excitation energy are getting lower and lower. The excitation energy and kinetic energy should be correlated. However, recently, F. Deák *et al.* [15,16] found from the coincident measurement that the differential relative population of IMF is nearly independent of its kinetic energy and has no strong dependence on the emission angle, and that most of the fragments are from the same emitter. It seems that the temperature does not change much during the particle emission process in the nuclear reaction. The nuclear temperature measured by the relative population method does reflect the situation of the nuclear reaction system at the freeze-out stage.

2. ISOTOPIC NUCLEAR TEMPERATURE

A new method for measuring the isotopic nuclear temperature was suggested by S. Albergo *et al.* in 1985 [17]. The physical basis of the method is relatively simple. The thermal and chemical equilibrium of the nuclear system is reached at a definite temperature, assuming that there is no interaction among single particles and composite particles. From the semi-classical method the density distribution of a particle with a charge number Z and mass number A is:

$$\rho(A, Z) = \frac{(2\pi m_0 AT)^{3/2}}{h^3}\omega(A, Z, T)\exp\left[\frac{Z\mu_p + (A-Z)\mu_n + B(A, Z)}{T}\right], \quad (1)$$

where $\omega(A,Z,T)$ is the internal partition function of the composite particle, μ_p and μ_n are the chemical potentials of protons and neutrons, respectively, and $B(Z,A)$ is the binding energy. Neglecting the influence of successive decay, the isotope yield ratio can be written as a function of nuclear temperature:

Table 1
Parameters a, b, and c for several selected pairs of isotopes.

$Y(A_1, Z_1)/Y(A_2, Z_1)$	$Y(A_3, Z_2)/Y(A_4, Z_2)$	a	b	c
^{3}He/^{4}He	^{6}Li/^{7}Li	2.18	−13.33	1.419×10^{-2}
	^{7}Li/^{8}Li	1.98	−18.54	2.066×10^{-2}
	^{9}Be/^{10}Be	0.38	−13.77	1.854×10^{-2}
^{6}Li/^{7}Li	^{7}Li/^{8}Li	0.91	−5.22	6.467×10^{-3}
	^{9}Be/^{10}Be	0.17	−0.44	4.343×10^{-3}
	^{10}B/^{11}B	0.39	4.21	-1.523×10^{-3}
^{7}Li/^{8}Li	^{9}Be/^{10}Be	0.19	4.78	-2.124×10^{-3}
	^{10}B/^{11}B	0.43	9.42	-7.990×10^{-3}
	^{11}B/^{12}B	0.56	1.34	-3.533×10^{-3}

$$R = \frac{Y(A_1, Z_1) / Y(A_2, Z_1)}{Y(A_3, Z_2) / Y(A_4, Z_2)} = a\frac{\omega(A_1, Z_1, T)\omega(A_4, Z_2, T)}{\omega(A_2, Z_1, T)\omega(A_3, Z_2, T)} \exp\left[\frac{\Delta A\mu_n + b}{T}\right], \tag{2}$$

where $a = (A_1A_4/A_3A_2)^{3/2}$; $b = B(A_1,Z_1) + B(A_4,Z_2) - B(A_2,Z_1) - B(A_3,Z_2)$; $\Delta A = A_1 + A_4 - A_2 - A_3$. When the composite particle is supposed to be at the ground state of internal excitation and $\Delta A = 0$, the nuclear temperature T_1 can be found as

$$R = a \exp(b / T_1), \tag{3}$$

The parameters a and b for different selected isotopes are listed in Table 1. The uncertainty of the nuclear temperature T_1 resulting from the uncertainty of the isotope ratio R is given as follows [18]:

$$\Delta T_1 / T_1 = -T_1\Delta R / (bR). \tag{4}$$

Many researches show the IMFs emitted in nuclear reactions are excited, so the contribution of the internal partition function should be taken into account. When identifying the protons and neutrons according to grand canonical distribution, the partition function can be written as follows:

$$\log\omega(A, Z, T) = \alpha_n N + \alpha_p Z - \beta E + \sum_{k=0}^{\infty} \frac{4(k+1)I_{2k}\{g_n^{(2k)}(\alpha_n / \beta) + g_p^{(2k)}(\alpha_p / \beta)\}}{(2k)!\beta^{2k+1}}, \tag{5}$$

where g_n and g_p are single-particle energy level densities of neutrons and protons, $\beta = 1/T$, α_n/β and α_p/β are their chemical potentials, respectively, and $I_n = \int_0^\infty \ln(1 + e^{-x})x^n dx$. If the Fermi energy of isotopes is assumed to be the same, the extracted nuclear temperature is written as T_2 and then

$$\frac{\omega(A_1, Z_1, T_2)\omega(A_4, Z_2, T_2)}{\omega(A_2, Z_1, T_2)\omega(A_3, Z_2, T_2)} = \exp\{-\beta_2(E_1 - E_2 - E_3 + E_4)\} = \exp[-\beta_2(E_1^* - E_2^* - E_3^* + E_4^*) + b\beta_2], \tag{6}$$

where the three quantities $\beta_2 = 1/T_2$, excitation energy E^*, and temperature T_2 are related by $E^* = K(T_2)T_2^2$. Since the energy level density parameter $K(T_2)$ is proportional to the mass number A of the nucleus [19], then we have:

$$R = a\exp(2b / T_2). \tag{7}$$

If the nuclear temperature is not too high, the derivatives of single-particle energy level densities can be neglected in Eq.(5), so only the contribution from $k = 0$ is considered and one obtains

$$T = [1 - \sqrt{1 - 8cT_1^2 / b}\ ]\ b / (2T_1c), \tag{8}$$

where T_1 is the temperature obtained by using Eq.(3). The parameter c is given by:

$$\begin{aligned} c = (\pi^2 / 3)\{&g_n[\mu(A_1, Z_1)] + g_p[\mu(A_1, Z_1)] \\ &+ g_n[\mu(A_4, Z_4)] + g_p[\mu(A_4, Z_4)] - g_n[\mu(A_2, Z_2)] \\ &- g_p[\mu(A_2, Z_2)] - g_n[\mu(A_3, Z_3)] - g_p[\mu(A_3, Z_3)]\}. \end{aligned} \tag{9}$$

The influence of the internal excitation partition function of IMF on the measurement of nuclear temperature is studied under the simplest zero-order approximation using two methods. Under the assumption of the Fermi gas model the single-particle energy level densities are $g_p = 3Z\varepsilon^{1/2}/\varepsilon_{pf}^{3/2}$, $g_n = 3N\varepsilon^{1/2}/\varepsilon_{nf}^{3/2}$, and the Fermi energies of protons and neutrons are $\varepsilon_{pf} = (2Z/A)^{2/3}\varepsilon_f$ and $\varepsilon_{nf} = (2N/A)^{2/3}\varepsilon_f$, respectively, with $\varepsilon_f = 38$ MeV. The obtained values of parameter c are given in 1. From the positive or negative sign of parameters c, one can see that after considering the zero-order correction of single-particle energy level density the measured temperature transits from the case of Eq.(7) to that of Eq.(3). The values obtained from Eq.(7) and Eq.(3) are the higher and lower limits of nuclear temperature extracted from isotope yield ratio, and the real nuclear temperature is between the two limits obtained from Eq.(7) and Eq.(3).

Using the local density approximation (LDA) at the Fermi energy the single-particle energy level density of protons and neutrons is

$$g_{LDA}(\varepsilon_f) = \frac{(3\pi^2 n)^{\frac{1}{3}}}{2\pi^2}\int \frac{2m}{\hbar^2}\rho^{\frac{1}{3}}(r)\mathrm{d}^3r\ . \tag{10}$$

The proton and neutron numbers are $n = Z/A$ and $n = N/A$, the density distribution of the nuclear matter is selected to be of the Fermi type [20]: $\rho(r) = \rho_0/\{1 + \exp[(r - R_0)/a_0]\}$, where the nuclear radius is $R = (0.978 + 0.0206A^{1/3})A^{1/3}$; the diffusion parameter $a_0 = 0.54$ fm; $\rho_0 = 3A/\{4\pi R^3[1 + (a_0\pi/r)^2]\}$. For the isotope ratio [^{3}He/^{4}He]/[^{6}Li/^{7}Li] the obtained parameter $c = 0.2167$. One can see from Fig. 1(a) that the internal excitation energy has strong influence on the measurement of isotope nuclear temperature. The physical reason of the approximate results $T = 1.2T_1$ [18] may be the influence of the internal partition function of IMF. From a comparison between the results of the zero-order partition function approximation calculation and the analytical solution of the Fermi model one can find the most important contribution already included in zero-order approximation.

3. RESULTS AND DISCUSSION

From the calculation it may be found that the internal excitation strongly influences the isotope nuclear temperature of IMF emitted in the decay process of a hot nucleus. When the influence of the

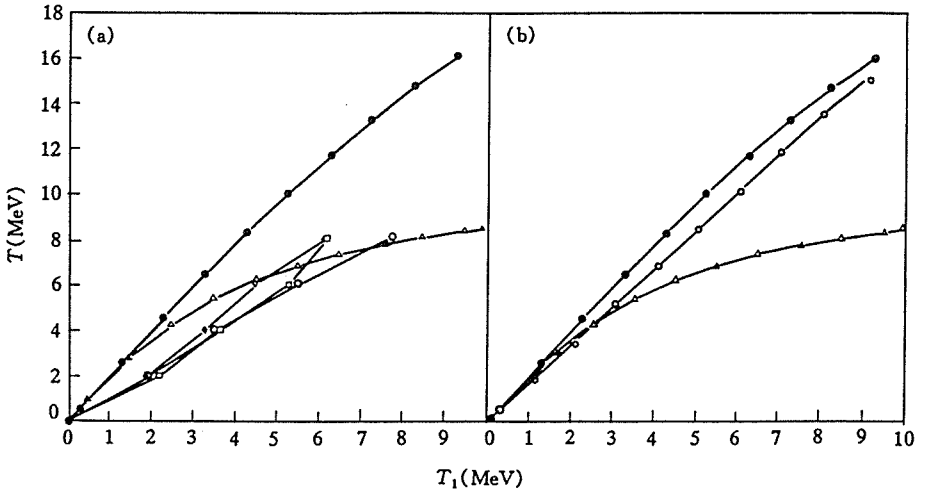

Fig. 1

The relation between nuclear temperature, calculated by using different methods, and isotope nuclear temperature. (a) Simulation calculation results from QSM (○ for $\rho_0/\rho = 0.1$, ◇ for $\rho_0/\rho = 0.5$), GEMINI (□), LDA (△), and the Fermi gas model (●) ($k = 0$); (b) results from the LDA approximation (△) and zero-order approximation on the basis of the Fermi model (○) corrected by the effect of internal partition functions to the isotope nuclear temperature and the analytical solution of the Fermi model (●).

internal partition function of IMF is neglected, under the assumption of equal Fermi energy of isotopes of IMF, the temperature extracted using Eq.(3) and the temperature extracted using Eq.(7) are the lower and higher limits. If the temperature is not too high, the zero-order approximation in partition function expansion is already good enough to describe its effect.

In comparison with other nuclear temperature extraction methods, the isotope nuclear temperature method is relatively simple and easier to do. However, a better isotope identification capability is required in the experiment. If the isotope identification is not good enough the yield of one isotope may decrease and instead the yields of neighboring isotopes may increase when calculating the isotope yields. This leads to a larger deviation in the ratio of isotope yields. In the case of phase transition, it is not clear whether the relation between excitation energy and nuclear temperature $E^* = K(T)T^2$ is still valid, and the validity of the isotope nuclear temperature measurement method still needs to be studied further.

REFERENCES

[1] L.P. Csernai and J.I. Kapusta, *Phys. Rep.*, **131**(1986), p. 223.
[2] E. Suraud, C. Gregoire, and B. Tamain, *Prog. of Nucl. and Particle Sci.*, **23**(1989), p. 357.
[3] G.J. Kunde *et al.*, *Phys. Lett.*, **B272**(1991), p. 202.
[4] C.A. Ogilvie *et al.*, *Phys. Rev. Lett.*, **67**(1992), p. 1214.
[5] Xu H.M. *et al.*, *Phys. Lett.*, **B182**(1986), p. 155.
[6] D. Hahn and H. Stöcker, *Nucl. Phys.*, **A476**(1988), p. 718.
[7] R.J. Charity *et al.*, *Nucl. Phys.*, **A483**(1988), p. 371.
[8] D.H.E. Gross, *Prog. Part. Nucl. Phys.*, **30**(1993), p. 155.
[9] J. Pochodzalla *et al.*, *Phys. Rev. Lett.*, **75**(1995), p. 1040.

[10] A. Chbihi *et al.*, *Ganil*, P95-24.
[11] Wang Hui *et al.*, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **21**(1997), p. 44.
[12] J. Pochodzalla *et al.*, *Phys. Rev. Lett.*, **55**(1985), p. 177.
[13] Xi Hongfei *et al.*, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **17**(1993), p. 294.
[14] Xi Hongfei *et al.*, *Nucl. Phys.*, **A552**(1993), p. 281.
[15] F. Deák *et al.*, *Phys. Rev.*, **C52**(1995), p. 219.
[16] F. Deák *et al.*, *Phys. Rev.*, **C39**(1989), p. 733.
[17] S. Albergo *et al*, *Nuovo Cimento*, **A89**(1985), p. 1.
[18] T. Möhlenkamp *et al.*, in: *XXXIII International Winter Meeting on Nuclear Physics, Jan. 1995, Bormio, Italy*, edited by I. Iori, p. 383.
[19] S. Shlomo, *Nucl. Phys.*, **A539**(1992), p. 17.
[20] J.W. Negele, *Phys. Rev.*, **C1**(1970), p. 1261.