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An improved thermometer for intermediate-mass fragments

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Abstract An improved thermometer (T_{IB}) is proposed for intermediate-mass fragments via the difference between isobaric yield ratios. The residual free energy of three isobars is replaced by that of the binding energy. The measured fragments in the 140*A* MeV ^{40,48}Ca + ^{9}Be (^{181}Ta) and ^{58,64}Ni + ^{9}Be (^{181}Ta) reactions are analyzed to obtain T_{IB} ranging from 0.6 to 3.5 MeV. T_{IB} is suggested to be a direct determination of temperature avoiding the fitting procedure.

Keywords Temperature · Intermediate-mass fragment · Isobaric ratio

1 Introduction

The measured fragments in heavy-ion collisions have a lower temperature than the primary fragments which are formed in the hot source. The Albergo isotopic thermometer has been used to extract the temperature based on the yields of protons, neutrons, and some light isotopes [1]. Also, the isotopic thermometer has been used to extract the temperature of larger isotopes, such as the carbon isotopes [2, 3] and intermediate-mass fragments (IMFs) [4, 5]. Other methods employed to study this temperature in heavy-ion collisions include the thermal energy method [6], excitation energy method [7], momentum fluctuation method [8], the correlation of two-particle relative moment [9], and kinetic energy spectra of light particles [4]. Recently, the isobaric ratio method has been proposed to extract temperature for IMFs [10].

In the thermodynamic models, temperature is one part of the probes and cannot be separated easily. In the isobaric yield ratio method, the symmetry energy coefficient is studied by using its ratio to the temperature (a_{sym}/T) for neutron-rich nucleus [11]. In this article, an improved thermometer is proposed to extract T of the IMFs which is based on the IYRs [12, 13].

2 Methods

Here, the canonical ensemble theory is adopted. Based on the grand-canonical limitation, the cross section $\sigma(A, I)$ of a fragment has the form of [14]

$$\sigma(A,I) = CA^{\tau}\exp\{[-F(A,I)+\mu_n N+\mu_p Z]/T\}, \tag{1}$$

where C and τ are constants; T is the temperature, $I = N - Z$ is the neutron excess; $\mu_n(\mu_p)$ is the chemical potential of neutron (proton); and $F(A, I)$ is the free energy of a fragment, which can be parameterized as the T-dependent mass formula [10, 15–18].

The IYR is defined between the yield of isobars with I and $I - 2$

$$\begin{aligned}\ln R(A,I,I-2) &= \ln\left[\frac{\sigma(A,I)}{\sigma(A,I-2)}\right] \\ &= [F(A,I-2)-F(A,I)+\Delta\mu]/T,\end{aligned} \tag{2}$$

where $\Delta\mu = \mu_n - \mu_p$. Similarly, for isobars with I +2 and I, one has

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$$\ln R(A,I+2,I) = \ln\left[\frac{\sigma(A,I+2)}{\sigma(A,I-2)}\right] = [F(A,I) - F(A,I+2) + \Delta\mu]/T. \quad (3)$$

$\Delta\mu/T$ for fragment changes very small, which has been shown in an isobaric ratio difference method [19–25], Thus, $\Delta\mu/T$ can be canceled out in the difference between isobaric yield ratios,

$$\ln R(A,I+2,I) - \ln R(A,I,I-2) = [2F(A,I) - F(A,I-2) - F(A,I+2)]/T. \quad (4)$$

The residual free energy is defined as $\Delta F \equiv 2\ F(A, I) - F(A, I-2) - F(A, I+2)$. If ΔF is known, T can be obtained. It has been proven that within the finite temperature range, ΔF between two isobars can be replaced by that of the binding energy for the fragments [13]. Following the assumption in Refs. [12, 13], the residual free energy ΔF can be replaced by the residual binding energy $\Delta B = 2\ B(A, I) - B(A, I-2) - B(A, I+2)$. From Eq. (4), the improved method to extract T based on the difference between IYRs (labeled as T_{IB}) is

$$T_{\mathrm{IB}} = \frac{2B(A,I) - B(A,I-2) - B(A,I+2)}{\ln R(A,I+2,I) - \ln R(A,I,I-2)}. \quad (5)$$

where $\Delta\ln R = \ln R(A, I+2, I) - \ln R(A, I, I-2)$ is defined for simplification. The binding energy in the AME12 will be adopted in the analysis [26].

3 Results and discussion

The fragments in the 140A MeV ^{40,48}Ca + ^{9}Be (^{181}Ta) and ^{58,64}Ni + ^{9}Be (^{181}Ta) reaction are adopted to verify the T_{IB} method. They were measured by Mocko et al. [27] at the National Superconducting Cyclotron laboratory, Michigan State University.

ΔB and $\Delta\ln R$ will be discussed separately, beginning with the distributions of ΔB for fragments in the 140A MeV ^{40,48}Ca + ^{9}Be and ^{58,64}Ni + ^{9}Be reactions (Fig. 1). For the $I = 1$ fragments, ΔB increases almost monotonically with A, while for fragments of $I = 3, 5, 7$, ΔB staggers on the relative small A side. The staggering in ΔB becomes smaller for the $A > 33$ fragments. ΔB for the $I = 9$ fragments shows a small staggering, but the staggering is more evident for the $A > 47$ fragments.

Secondly, $\Delta\ln R$ for related isobars in the 140A MeV ^{40,48}Ca + ^{9}Be (^{181}Ta) and ^{58,64}Ni + ^{9}Be (^{181}Ta) reactions is plotted in Fig. 2. For the $I = 1$ fragments, $\Delta\ln R$ almost keeps constant on the small A side, but increases with A at $A > 40$, with some staggering at $A > 30$. For the fragments of $I = 3, 5, 7$, an obvious staggering appears in $\Delta\ln R$ on the small A side, but it staggers little when A is relative large.

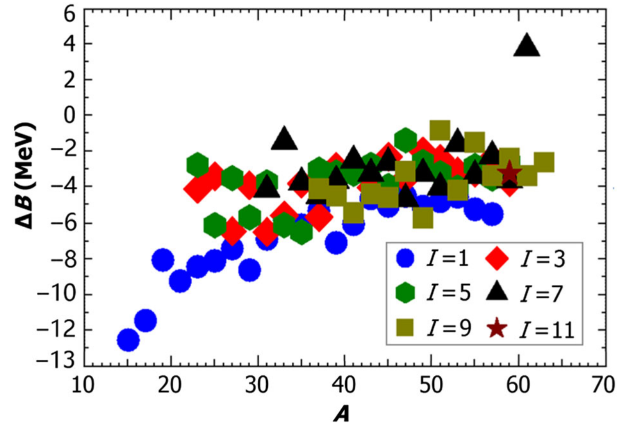


Fig. 1 (Color online) ΔB for the fragments in the 140A MeV ^{40,48}Ca + ^{9}Be (^{181}Ta) and ^{58,64}Ni + ^{9}Be (^{181}Ta) reactions

The target (^{9}Be and ^{181}Ta) shows very little influence on $\Delta\ln R$. In general, the distribution of ΔB and $\Delta\ln R$ is similar in shape.

Finally, we use ΔB and $\Delta\ln R$ in 140A MeV ^{40,48}Ca + ^{9}Be (^{181}Ta) and ^{58,64}Ni + ^{9}Be (^{181}Ta) reactions to calculate T_{IB} (Fig. 3). T_{IB} for the $I = 1$ fragments is almost constant at 1.5 MeV. T_{IB} for $I = 3$ staggers for small A fragments, but becomes small and constant at $A > 35$. T_{IB} for $I = 5$ staggers, too, in a small manner though. But the staggering becomes larger again for $I = 7$ and $I = 9$ fragments. For most of the $I > 3$ fragments, the T_{IB} values range from 0.6 to 3.5 MeV, which agrees with the temperatures extracted by the IYR method [12, 13]. Only for some fragments of very rich neutrons, the T_{IB} values are large. This agrees with the results in the canonical ensemble theory to estimate the mass of neutron-rich copper isotopes at $T = 2.2$ MeV [14]. Great difference can be seen between the T_{IB} values for the reactions using ^{9}Be and ^{181}Ta targets when I is large ($I = 7$ and 9), showing obvious target effect.

4 Summary

An improved isobaric ratio thermometer (T_{IB}) for intermediate-mass fragments has been proposed based on the difference between IYRs, in which the residual free energy is replaced by the residual binding energy among these isobars. In contrast to the IYR thermometer, T_{IB} is directly obtained from the yields of fragments and avoids the fitting procedure, which serve as a direct probe of temperature. T_{IB} of the odd I fragments in the 140 MeV ^{40,48}Ca + ^{9}Be (^{181}Ta) and ^{58,64}Ni + ^{9}Be (^{181}Ta) reactions has been obtained. The values of T_{IB} for most considered IMFs are low. There is some inference that for similar reactions with different asymmetries, T_{IB} can be assumed

Fig. 2 (Color online) $\Delta \ln R$ for the fragments in the 140A MeV $^{40,\,48}$Ca + ^{9}Be (^{181}Ta) and $^{58,\,64}$Ni + ^{9}Be (^{181}Ta) reactions

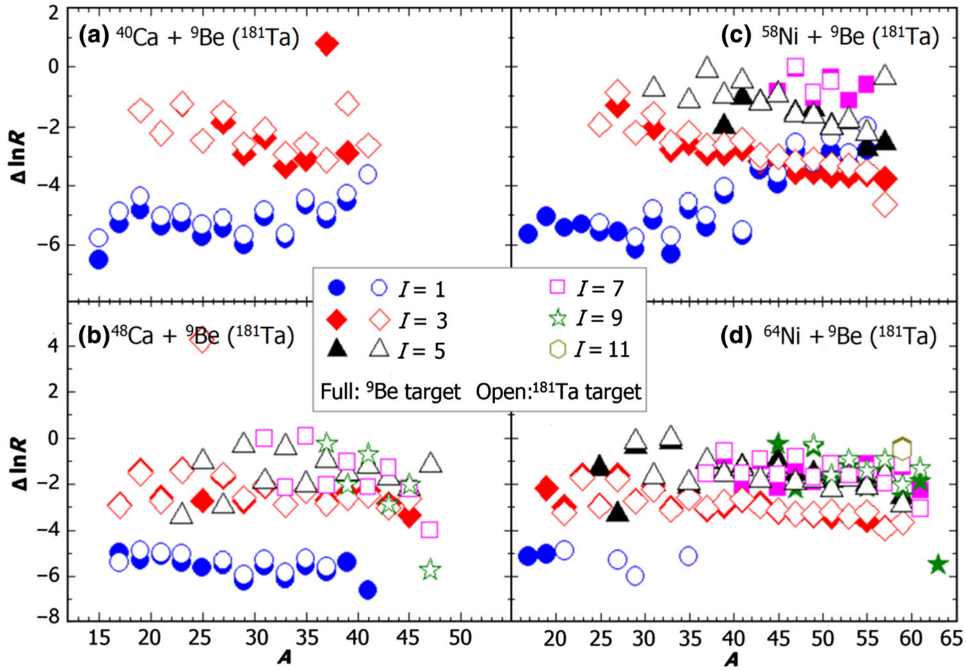
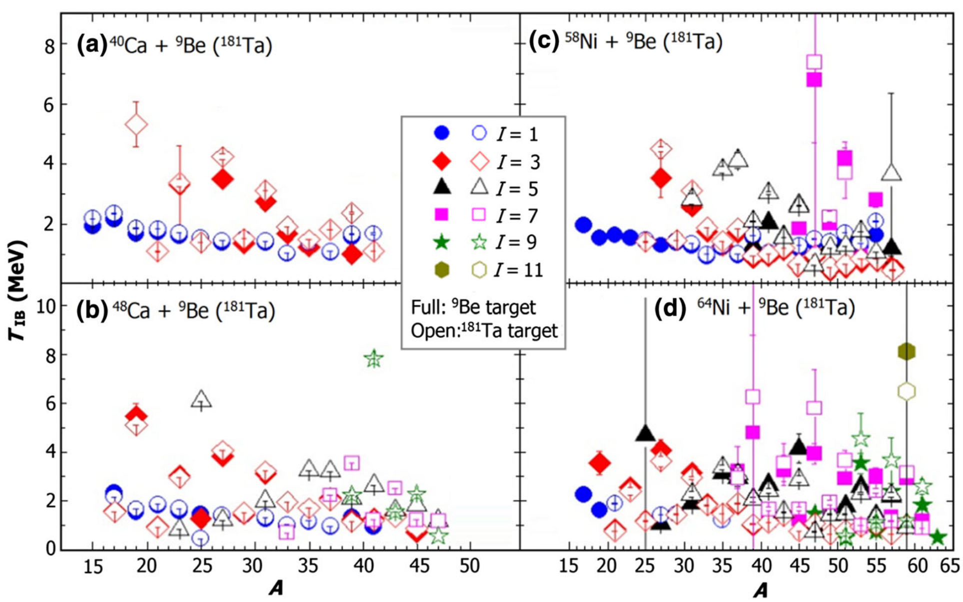


Fig. 3 (Color online) T_{IB} for the fragments in the 140A MeV $^{40,\,48}$Ca + ^{9}Be (^{181}Ta) and $^{58,\,64}$Ni + ^{9}Be (^{181}Ta) reactions



as the same, so the assumption is reasonable that the temperatures in two similar reactions are similar.

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