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NUCLEAR TEMPERATURE MEASUREMENTS WITH ISOTOPIC THERMOMETER *

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We study the corelation between "apparent" nuclear temperatures which can be measured in an experiment and "real" ones within the sequential statistical model. We extract temperature from slopes of kinetic energy spectra of light charged particles and from isotopic double ratios. We find that due to the chain of subsequent emissions the "apparent" temperature significantly differs from initial (average) temperature. We also find that the model of simple statistical evaporation works very well even for very high excitation energies.

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1. Introduction

It was already shown at this school [1, 2] how to measure nuclear temperature and what are the newest results of such measurements. Péter showed the caloric curves measured in the ^{36}Ar + ^{58}Ni reaction at 95MeV/A with the INDRA 4π detector [1]. There are significant differences between them, both within one method (left side of Fig. 2 in [1]) and between two methods used (left-right sides of Fig. 2 in [1]). We also have seen that one obtains different caloric curves applying the same "thermometer" to different reactions [2]. Using yet another method of temperature measurements based on the excited state population one obtain very low temperatures even for excitation energy as high as 15 MeV/A [2].

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This puzzling picture rises the question of the relationship between "apparent" temperatures and the initial ones. Apart from dynamical effects, there are two mechanisms which influence the "apparent" temperature:

1. Emission chain — the excited nucleus lowers its temperature after each act of emission. The higher is the excitation energy the longer is the emission chain and in consequence the bigger is the discrepancy between initial and average emission temperature.
2. Secondary decay (side-feeding) — the higher is the excitation energy, the higher is the probability of emitting particles in excited, particle unstable states. This process removes this particle from our measurements and increases the number of other particles, influencing also their energy spectra.

We will try to understand how these processes affect an "apparent" temperature which can be measured experimentally.

2. Model

We applied the standard evaporation model [3]. The charge (or mass) of the emitter is chosen according to the experimental distribution, its excitation energy is chosen randomly and the temperature is calculated from the formula $T = \sqrt{10E^*}$. Fragments with $Z<6$ and $A<10$ are emitted in discrete states. Heavier fragments decay until excitation energy is exhausted or until they decay into fragments with $Z<6$ and $A<10$. All discrete states decay at the end of calculation.

The maximum width of the states included in the calculations is a free parameter of the code. The results presented in Fig. 1 are obtained with $\Gamma < 2$MeV (which corresponds to life time < 100 fm/c).

3. Results

To demonstrate the role of emission chain and side-feeding we made calculations without the evaporation chain, simply stopping the code after the first act of emission - we call it first chance emission (FCE).

To use our isotopic thermometer in the right way (according to the Albergo formula [4]) we have to use only fragments emitted in the ground state. In this way we have an access to the initial temperature (Fig. 1a,b). The two next steps of our calculations (not shown) are: 1^o inclusion of all excited fragments, and 2^o decay of excited fragments. We observe a decrease of the "apparent" temperature calculated from isotopic double ratios. This change is however quite moderate and the calculated temperature qualitatively follows the initial one. The slope parameters are slightly lower when including side-feeding.

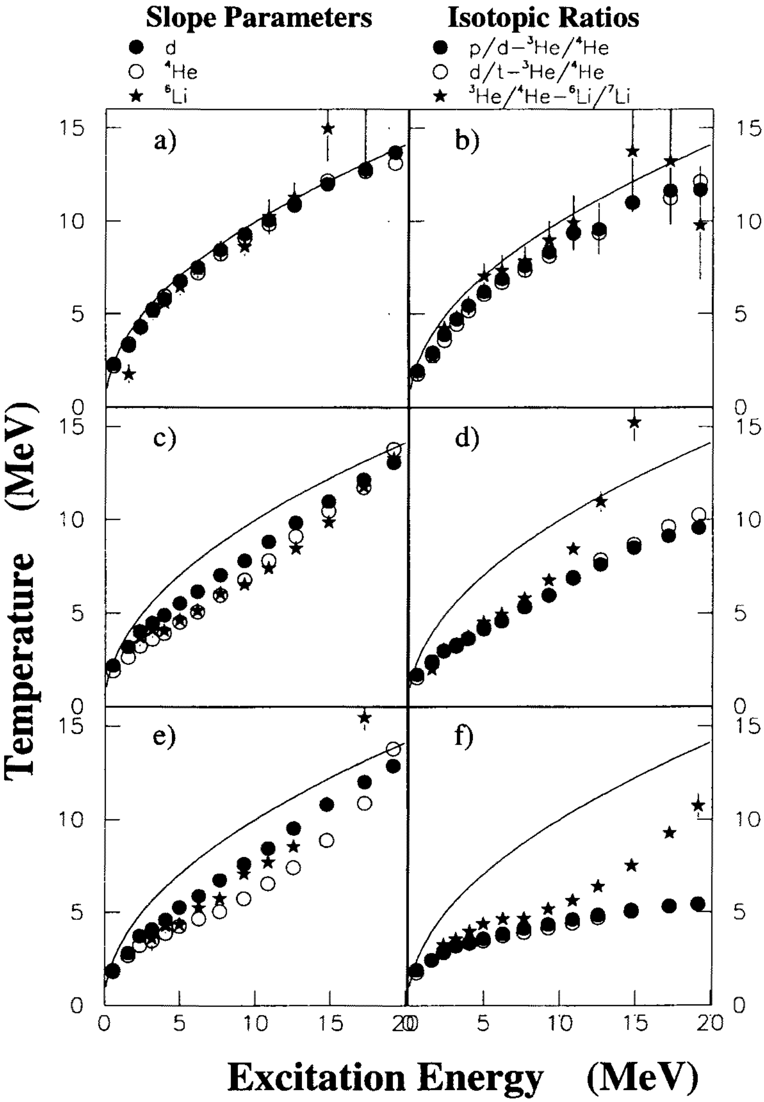

Fig. 1. Caloric curves calculated with an evaporation code. Temperatures are extracted from slope parameters (left hand side - a,c,e) and double isotopic ratios (right hand side - b,d,f) at different stages of the calculation: a,b) FCE taking into account only particles emitted in their ground state. before decay of discrete states c,d) Emission Chain taking into account all particles before decay of discrete states e,f) Emission Chain after decay of discrete states. The solid line represents the relation between T and E*: $T = \sqrt{10E^*}$

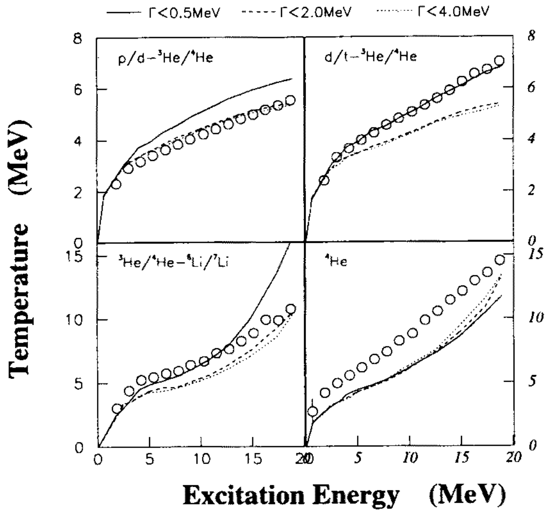

Fig. 2. Dependence of the calculated "apparent" temperature on the maximum width of discrete states included in the calculations. Points represents experimental data [5].

A quite different situation is obtained when the full evaporation chain is studied. When the decay of discrete states is not taken into account (Fig. 1d) two of the three analysed caloric curves increases almost linearly but the "apparent" temperature stays under the initial value. The temperature obtained from He-Li isotopic ratio behaves quite differently. At some excitation energy it starts to increase fast. This unexpected rise is caused mainly by the increased of production rate of ^{4}He and ^{7}Li when evaporation chain is switched on. The secondary decay of excited fragments considerably increase the number of ^{4}He in the final state which lowers significantly the "apparent" temperature (Fig. 1f) and the calculated curve is very similar to the experimental one.

The slope parameters are much less influenced by both disturbing processes (Fig. 1c,e). Especially deuterons and protons (not presented) keep a good memory of the initial temperature. For heavier elements there is a strong increase of temperature at high excitation energy.

Having the width of all discrete states included in the code we have the possibility to study the influence of in(ex)cluding some states on the "apparent" temperature. In Fig. 2 we present results including states with Γ lower than 0.5, 2.0 and 4.0 MeV (which correspond to 400, 100 and 50 fm/c life time) and compare them with the data [5].

To reproduce temperatures from p/d-^{3}He/^{4}He one has to include very broad (short living) states, while d/t-^{3}He/^{4}He requires to exclude states with Γ >0.5 MeV. Temperatures from ^{3}He/^{4}He-^{6}Li/^{7}Li suggest a change in the time scale: broader states should be included as excitation energy increases. It seems that each "isotopic thermometer" is consistent with different "time scales" but this point is not established since the widths of several high excited levels are not well known and some levels are likely not known at all. A value of $\Gamma \approx 2$ MeV gives a reasonable fit for all.

4. Conclusions

Both emission time sequence and feeding from secondary decays have large effects on caloric curves measured with "isotopic thermometers". Secondary decays (side-feeding) reduce apparent temperature values while emission chain changes the shape of the caloric curve for He-Li thermometer in such a way that it could easily mimic a behaviour similar to a liquid-gas phase transition.

The simple model of evaporation which includes emission of excited fragments in discrete states works well even for very high excitation energies. The temperatures obtained with different "isotopic thermometers" might be related to different time scales of particle emission and decay. These time

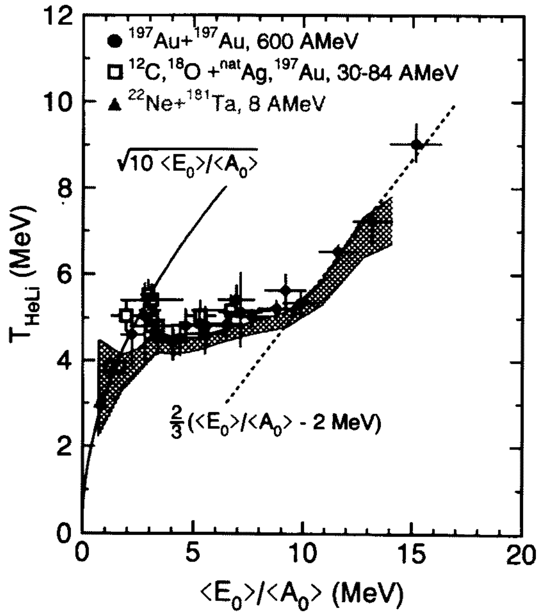

Fig. 3. Results of theoretical calculations made with our evaporation code (the shaded area represents statistical errors) compared with the experimental data [2].

scales varies from 50 fm/c (which corresponds to sudden disintegration) to 400 fm/c (sufficient for statistical evaporation).

Finally, we emphasize the predicting power of this model by presenting our calculations for ALADIN data [6] (Fig. 3). The only change we had to make in the code was to include the dependence of the source mass on its excitation energy, which we read from experimental points presented in [6] (A/Z ratio 2.5 for all E^* was assumed).

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