Eur. Phys. J. A **8**, 355–360 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

Nuclear temperature measurements with the double isotope ratio technique: Influence of the experimental conditions

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Received: 6 October 1999 / Revised version: 6 March 2000
Communicated by C. Signorini

Abstract. The dependence of the nuclear temperatures of highly excited systems, extracted by means of the double ratios of the emitted isotopes, on the experimental conditions is investigated. Experimental data obtained in the Xe+Cu 30 MeV/nucleon reaction are used to study the sensitivity of the method and the effects of the energy thresholds on the obtained temperature values. We find that the temperatures extracted using the He/Li ratios can be strongly influenced by the experimental energy thresholds which are different for different elements. These distortions depend on the velocity of the emitting system and on the detection angle and therefore particular care is needed in the choice of the detectors in those experiments in which velocities are low and angles are large. The use of four isotopes of the same element make negligible such effects.

PACS. 21.65.+f Nuclear matter – 25.70.Pq Multifragment emission and correlations

1 Introduction

In intermediate-energy heavy ion reactions ($10 < E/A < 100$ MeV/nucleon) several different decaying systems are formed depending on the entrance channel and on the impact parameter. These systems emit fragments (light, intermediate and heavy mass fragments), *i.e.* they behave as fragment sources which differ in size, shape and excitation energy. In particular for excitation energies above 2 MeV/nucleon multifragmentation appears as one of the possible de-excitation process [1–12].

To gain more insight into the characteristics of the intermediate mass fragment emitting sources, one has to measure the temperatures of well-defined and experimentally identified systems, with different excitation energy and size, using reliable thermometers. Temperatures extracted from the isotopic abundances have stimulated a large body of experimental and theoretical work, both supportive and critical of the thermometric technique employed [13–21].

Starting from the results of temperature measurements of nuclear systems formed in Xe+Cu 30 MeV/nucleon collisions we discuss here how the experimental constraints, such as kinematical limits and detector inefficiencies, could directly affect temperature measurements when the double isotope ratio technique is used. When the mass identification is carried out with the $\Delta E - E$ technique, it has to be taken into account that the energy threshold is different from one isotope to another, and therefore, the temperature values extracted by means of the method of double isotope-yield ratio, could be strongly affected by the different energy range of each single isotope. The aim of the present paper is to study how the experimental conditions, such as the detectors thickness, the velocities of the emitting systems, and detection angles, and their interplay influence the temperature measurements. Such an investigation has been carried out exploiting the experimental data on the isotope production and simulating different energy thresholds.

In sect. 2 a brief description of the temperature measurement technique and of the experimental conditions are given; in sect. 3 the results, regarding the induced distortions on temperature measurements are presented and discussed. The conclusions are drawn in sect. 4.

2 Experimental method

2.1 Nuclear temperature measurements

The reliability of the double ratios of isotope yields [22] method is based on the following conditions:

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i) free nucleons and composite fragments are contained within a certain volume V at a single temperature T and are in thermal equilibrium;

ii) it is possible to use the Maxwell-Boltzmann statistics;

iii) the system has reached the chemical equilibrium;

iv) the experimental yield of a fragment is proportional to its density inside the volume V;

v) all detected nuclei originate from a single source.

The double ratio R of the yields Y of four isotopes in their ground states, prior to secondary decay, is then given by

$$R = \frac{Y(A_1, Z_1)/Y(A_1+1, Z_1)}{Y(A_2, Z_2)/Y(A_2+1, Z_2)} = \frac{e^{B/T}}{a}\,, \qquad (1)$$

where a is a constant related to spin and mass values, $B = BE(Z_1, A_1) - BE(Z_1, A_1+1) - BE(Z_2, A_2) + BE(Z_2, A_2+1)$, and $BE(Z, A)$ is the binding energy of a nucleus with charge Z and mass A [22].

Moreover the emitting source is considered not to have angular momentum and any dynamical behaviour (such as compression and expansion of the system, pre-equilibrium emission, etc.) is neglected.

As the fragments can be highly excited, secondary decays from higher-lying states of the same and heavier nuclei cannot be neglected: they can lead to sizable corrections to the measured ratios R [23]. To reduce the sensitivity to such corrections, it is advisable to choose cases for which $B \gg T$, since the uncertainties on T are proportional to $\frac{T}{B}$.

Once the set of data coming from a single source is defined, the isotopic resolution allows the extraction of temperatures from a high number of isotope ratios. Since the goal of this paper is to understand the effects induced by instrument efficiencies, we limit here the discussion to two of the most used thermometers, ^{6}Li/^{7}Li-^{3}He/^{4}He ($T_{\rm HeLi}$) and ^{12}C/^{13}C-^{11}C/^{12}C (T_C) [13,18–20].

2.2 Experimental set-up and the measurements

The data used in the present study refer to measurements performed at the National Superconducting K1200 Cyclotron Laboratory of the Michigan State University. The Xe+Cu at 30 MeV/nucleon [28] reaction was investigated with the aim of observing the characteristics of the nuclear systems formed in central and peripheral collisions. To this end, temperatures and excitation energies were measured.

The angular range $3^\circ < \theta_{\rm lab} < 23^\circ$ was covered by the *MULTICS* array [24]. It consisted of 48 telescopes, each of which was composed of an Ionization Chamber (IC), a silicon position-sensitive detector (Si, 500 μm thick) and a CsI(Tl) crystal. Typical energy resolutions were 2%, 1% and 5% for IC, Si and CsI, respectively. Energy calibrations were obtained by irradiating each telescope with low intensity direct beams of ^{4}He, ^{12}C and ^{16}O at 40 MeV/nucleon. The energy resolution of the silicon detectors allows for mass discrimination by means of the $\Delta E - E$ technique [25]. A good mass resolution for light isotopes (up to carbon) was obtained (see for instance fig. 1 of ref. [21]). Energy thresholds for mass identification of 8.5, 10.5, 14 MeV/nucleon were achieved for ^{4}He, ^{6}Li and ^{12}C nuclei, respectively.

Light charged particles and fragments with charge up to $Z = 20$ were detected at $23^\circ < \theta_{\rm lab} < 160^\circ$ by the phoswich detectors of the MSU *Miniball* hodoscope [26]. The charge identification thresholds were about 2, 3, 4 MeV/nucleon in the *Miniball* for $Z = 3, 10, 18$, respectively. The geometric acceptance of the overall array was greater than 87% of 4π.

2.3 Data selection

Since the method of double ratios of isotope yields [22] requires that the considered fragments be emitted from the same source, we adopted a procedure of data analysis which allowed to identify the emitting systems and assured that all the selected fragments, used to extract temperature values, could be safely assigned to well-defined sources. Furthermore we selected events for a given range of the impact parameter and verified that the reconstructed sources emitted fragments isotropically as expected for thermal equilibrium.

The multiplicity of detected charged particles (Nc) was used for the impact parameter b selection [27]:

$$\hat{b} = b/b_{\rm max} = \left(\int_{Nc}^{+\infty} P(N'c)\mathrm{d}N'c\right)^{1/2}.$$

Here $P(Nc)$ is the charged particle probability distribution and $\pi \cdot b_{\rm max}^2$ is the measured reaction cross section for $Nc \geq 3$.

A careful check on the identification of the sources and investigations on their characteristics was performed also studying the angular and energy distributions [21,28].

In the following the discussion will be focused on the temperature measurement of the quasi-projectile (QP) emitting source, highly excited in peripheral collisions ($\hat{b} > 0.8$, E^*=4 MeV/nucleon) [28]. In this impact parameter range the emitting systems (QP, quasi-target and mid-rapidity source, if formed) have quite different relative velocities and it is possible to distinguish their own decay products.

In order to identify the fragments coming from a common source, strong constraints on the data were necessary [21,28]. In particular, only fragments emitted in the forward direction with respect to the QP frame ($\theta < 60^\circ$) were accepted for the analysis (the QP moves with a velocity of 6.3 cm/ns in the laboratory frame). Such constraints allow to bypass problems due to the mixing of fragments coming from different sources (the quasi-target and mid-rapidity sources are present inside the same event) as well as inefficiencies existing at backward emission angles (in the laboratory frame fragments emitted backwards are less energetic and below the mass identification threshold). With these prescriptions it is possible to select a well-defined set of data, while expecting negligible distortions due to other experimental problems.

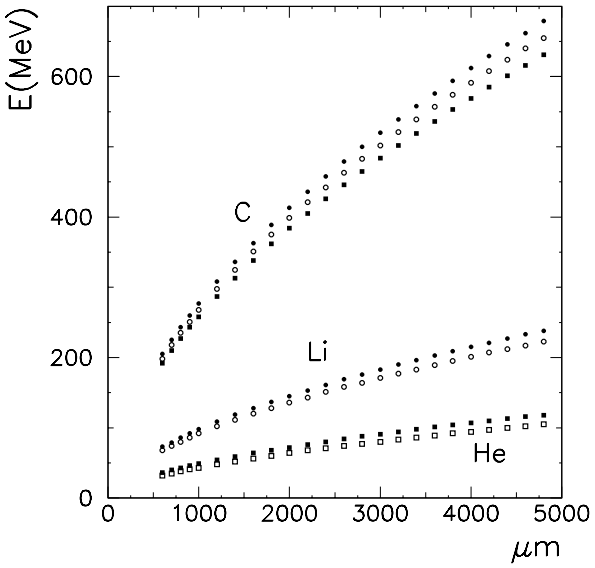

Fig. 1. Energies necessary to punch through increasing silicon thicknesses ($Z = 2$: ^{3}He open squares, ^{4}He full squares; $Z = 3$: ^{6}Li open circles, ^{7}Li full circles; $Z = 6$: ^{11}C full squares, ^{12}C open circles, ^{13}C full circles.

3 Results

In order to test the influence of the energy threshold for mass identification when applying eq. (1), the incident energy necessary to punch through increasing thicknesses of the ΔE silicon detector was first evaluated. This thickness has to include all the other layers preceding the stop E detector, used for mass identification by means of the well-known $\Delta E - E$ technique. In fig. 1 the minimum incident energy necessary to punch through a silicon equivalent thickness is plotted for different atomic species as a function of the thickness itself.

Energy loss calculations were performed referring to Anderson and Ziegler studies [25]. As expected fig. 1 shows a strong dependence on the atomic number Z and a weaker one on the mass A of the incident ion.

In fig. 2 the experimental energy distributions of the same fragments in the QP frame and in the laboratory frame are shown, on left and right side, respectively.

The energy distributions in the QP reference frame show similar shapes and slopes (by the way, this can be seen as a probe of a careful source identification [21,28]); on the contrary the energy distributions in the laboratory frame are shifted towards higher energy values, the shift being larger for heavier isotopes. In fact in the laboratory frame one has to consider the contribution of the QP emitting source motion to the kinetic energy. This additional kinetic energy depends on the velocity of the QP ($v_{\rm QP} = 6.3\,$cm/ns in the present experimental situation [28]), on the mass of the considered isotope and on the detection angle. Limiting the discussion to forward angles, as in the studied experimental data, this means that, for instance, ^{4}He, ^{7}Li, ^{12}C own at least $\simeq$80, $\simeq$150, $\simeq$ 250 MeV, respectively. This shift implies that up to a ΔE thickness $\simeq$2500, $\simeq$2200, $\simeq$900 μm (for ^{4}He, ^{7}Li and ^{12}C, respectively) no significant cut is present in the energy distributions spectra and experimental data can be safely used for temperature determination.

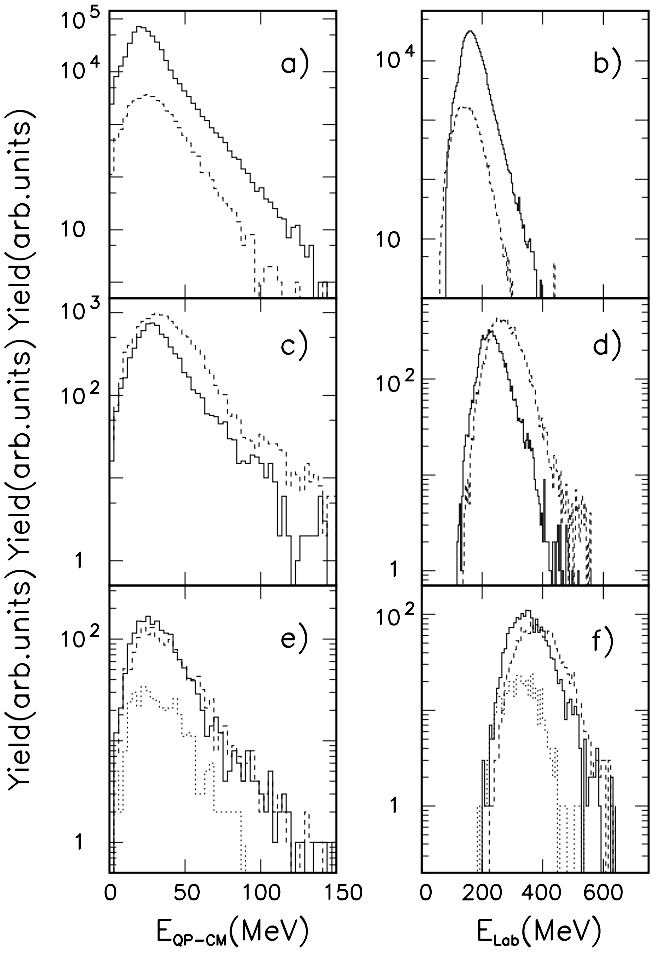

Fig. 2. Energy distributions in the QP reference frame (left panels) and in the laboratory frame (right panels): (a-b) ^{3}He dashed and ^{4}He full lines; (c-d) ^{6}Li full and ^{7}Li dashed lines; (e-f) ^{11}C dotted, ^{12}C full and ^{13}C dashed lines.

It is clear that for the experiment which we are dealing with, the energy thresholds do not affect the obtained temperature values, however, it is evident that higher energy thresholds or different experimental conditions, such as lower source velocities or large detection angles, can produce differences in the total yield used in eq. (1) and influence the temperature value.

To have more insight into the role played by the energy threshold, *i.e.* by the thickness of the ΔE detector, we analyzed the experimental data performing different energy cuts, *i.e.* simulating different experimental energy thresholds as due to a different thickness of the ΔE detector. The results of this procedure are shown in fig. 3, where the experimental yield ratios R between isotopes of the same atomic number are shown as a function of the silicon equivalent thickness preceding the stop detector (*i.e.* for increasing incident energy thresholds). Only fragments with energy higher than that necessary to punch through the ΔE detector were considered to evaluate R.

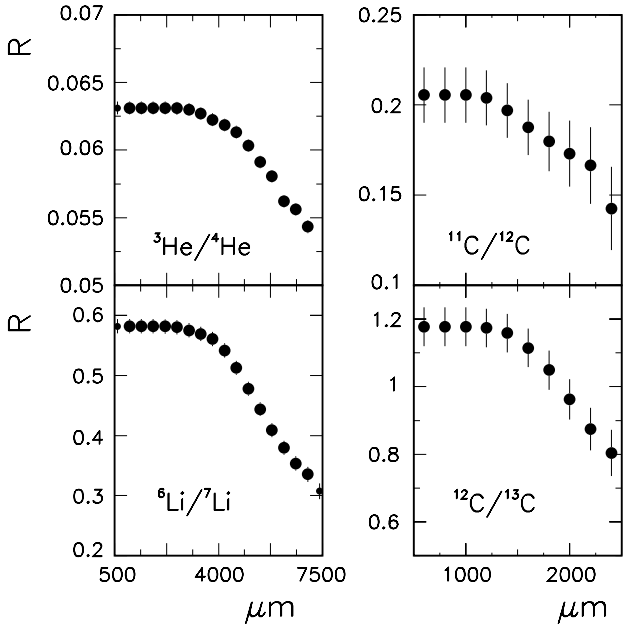

Fig. 3. Yield ratios R between isotopes of the same atomic species as a function of the silicon thickness preceding the stop detector.

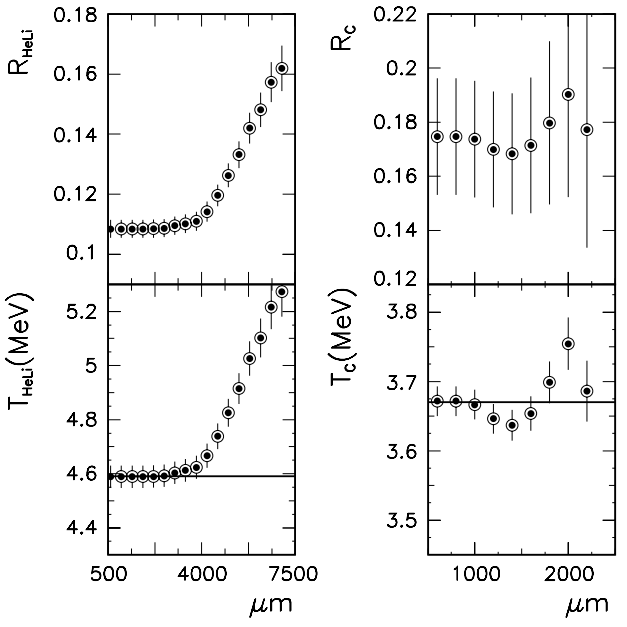

Fig. 4. Double ratio of isotope yields and related temperatures for the two considered thermometers as a function of the silicon thickness preceding the stop detector.

The decreasing behaviour of the ratios as a function of the ΔE thickness, is due to the fact that the lighter ions (which contribute to the numerator of R) have in the laboratory frame energy distributions relatively less expanded towards the higher values than the heavier ones (which contribute to the denominator of R).

From these experimental single isotope ratios, the double ratios of isotope yields and the corresponding temperatures have been extracted and their values are shown in fig. 4 as a function of the silicon thickness. The horizontal lines correspond to the temperature values extracted from non-distorted distributions [28]. One can clearly see that no particular distortion appears in the carbon thermometer: threshold effects do not play a significant role when dealing on double isotope ratios at fixed Z value. On the contrary, the temperature measurements involving He and Li isotopes can be influenced by the energy cuts. A strong dependence appears around 4 mm; for this thickness energies higher than $\simeq$100 and $\simeq$200 MeV are necessary to punch through, for $Z = 2$ and $Z = 3$, respectively. These energy values correspond to the maxima of the energy distributions and, therefore, the distorsions begin to play a significant role. Anyhow distorsions appear in fig. 4 only for really thick ΔE detectors, as for instance lithium-drifted silicons (the typical thickness is 3-5 mm) in multi-element telescopes. This holds for the data discussed here, *i.e.* for isotopes forward emitted by a source travelling at $v_{\rm QP} = 6.3\,$cm/ns. However, the energy thresholds are largerly influenced by the contribution of the emitting source motion to the total energy and the ΔE thickness for which distorsions arise becomes smaller for slower emitting sources (lower beam energies or higher dissipation in the reaction). As an example, for the reaction here considered at a QP velocity of 5.6 cm/ns (*i.e.* the velocity of the QP system formed in mid-peripheral collisions at $\hat{b} \approx 0.4$ with an expected excitation energy $\approx$6 MeV/nucleon) the kinetic energies of $Z = 2$, 3 and 6 fragments are at least $\simeq$65, $\simeq$115, $\simeq$ 200 MeV, respectively. The corresponding thicknesses of punching through are 1700, 1300 and 500 μm. If for the same considered system we have a beam energy of 20 MeV/nucleon, then, the QP emitting sources have expected velocities of 5 cm/ns (thinking at the 80% of the projectile velocity [13]). In this case the kinetic energies of the emitted fragments are at least $\simeq$50 ($Z = 2$, thickness of 1000 μm), $\simeq$90 ($Z = 3$, 850 μm), $\simeq$155 MeV ($Z = 6$, 350 μm).

In the cases where the source velocity is not high enough to give its decay products a strong burst, sufficient to safely overcome the energy thresholds, an additional study on the phase space is needed.

In order to analyze how the different experimental conditions affect the isotope yields and, therefore, the temperature values, we built up a Montecarlo simulation in which a source emits fragments isotropically in its c.m. frame and with energy distributions given by the experimental ones (see fig. 2a), c), e)). Therefore, we have studied the laboratory energy spectra of each considered (Z, A) product as a function of the velocity of the source and of the detection angle. We report here the results obtained for three values of the source velocity and for the case in which the decay products are emitted by the QP source with the Maxwellian slopes given in ref. [28]. In fig. 5 the calculated energy distributions for ^{4}He (left panels) and ^{7}Li (right panels) with different angle selections are presented for $v_{\rm QP} = 6.3\,$cm/ns that is the experimental situation presented here. In the first row the whole calculated energy distribution is shown. In the middle row the full lines refer to the energy distributions as seen by detectors cov-

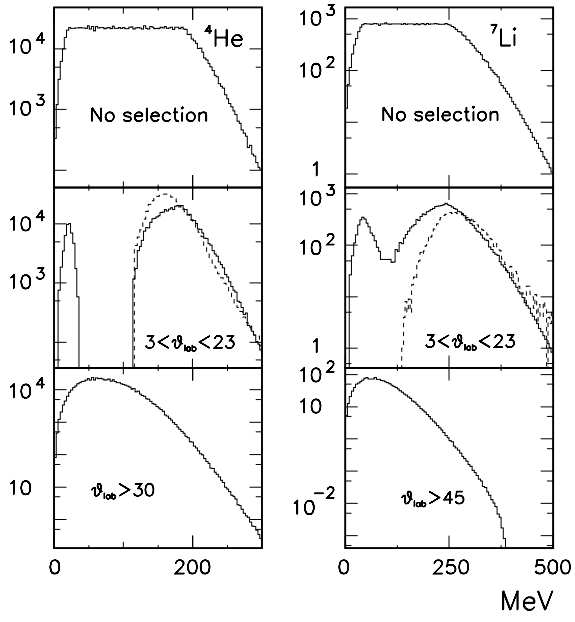

Fig. 5. Energy distributions for different emission angle ranges in the laboratory frame.

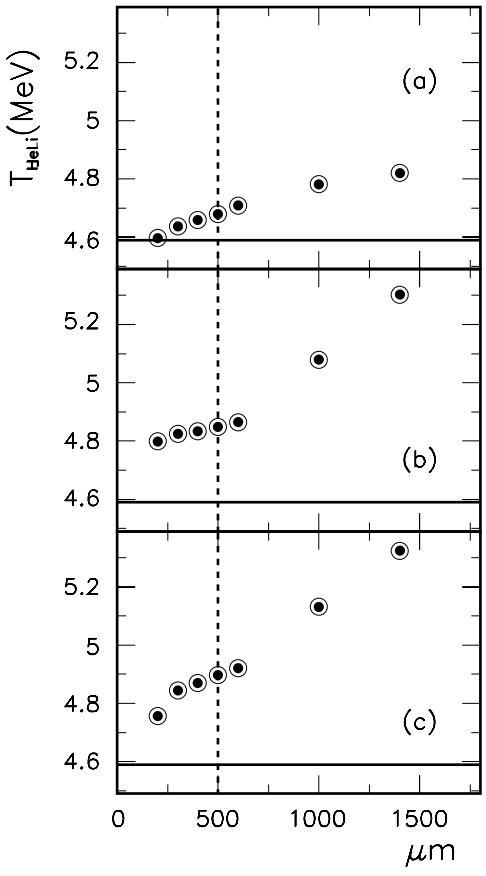

Fig. 6. Double ratio of isotope yields and related temperatures for the $T_{\rm HeLi}$ thermometer as a function of the silicon thickness preceding the stop detector: a) $v_{\rm QP} = 6.3\,$cm/ns, b) $v_{\rm QP} = 5.6\,$cm/ns, c) $v_{\rm QP} = 5.0\,$cm/ns. Only fragments emitted at angles higher than 30° in the laboratory frame are considered.

ering in the laboratory frame angles between 3 and 23° as for the experimental data of ref. [28] (but without energy threshold cuts); the dashed lines refer to the obtained experimental energy distribution [28]; in this case the temperatures were extracted performing a careful study on angular and energy distributions since the phase space has to be uniformly measured for all the investigated ions [21,28]. The last row presents the expected energy distributions considering only angles higher than 30° and 45° in the laboratory frame for ^{4}He and ^{7}Li, respectively. In this case the energy distributions mainly cover values for which the effects of energy threshold in the mass identification take place heavily. Thus it is clear, already at first sight, that temperature measurements result less reliable if obtained from experimental data collected with detectors placed at large angles.

To see it more quantitatively, we considered different energy thresholds due to different detector thicknesses and we extracted the temperatures from the data collected at angles higher than 30° as a function of the detector thickness for the given source velocity (fig. 6a). In fig. 6b) and c) we show the same results for different source velocities. For fast QP emitting sources ($v_{\rm QP} = 6.3\,$cm/ns, fig. 6a) it is evident that little differences on extracted $T_{\rm HeLi}$ values appear even for small thicknesses (200 μm); however in this case distortions remain of the order of 1-2% dealing on small thicknesses (up to 500 μm). The situation is different for slower emitting sources: systematic errors of 5% ($v_{\rm QP} = 5.6\,$cm/ns, fig. 6b) and 10% ($v_{\rm QP} = 5\,$cm/ns, fig. 6c) take place, even for ΔE detectors relatively thin (500–600 μm).

If, for instance, the measurements are devoted to the study of a possible liquid-gas phase transition, where temperatures range between 4 and 6 MeV, systematic errors of this kind could give rise to important difficulties in data interpretation.

In conclusion, one has to stress that as in experiments in which temperature measurements are performed with detectors placed at large laboratory angles, a careful data selection, that takes into account the efficiency of phase space covered, is required. The importance of this problem increases when the sources are relatively slow, for instance for QP with low energy beam (<20 MeV/nucleon) or for central collisions in which incomplete fusion takes place ($v_{\rm QP} = 5.2\,$cm/ns, for Xe+Cu 30 MeV/nucleon).

4 Conclusions

In summary isotope yields emitted from highly excited nuclei produced in Xe+Cu 30 MeV/nucleon collisions were measured in experiments performed at the National Superconducting K1200 Cyclotron Laboratory of the Michigan State University.

Temperature measurements of well-defined and experimentally defined emitting sources have been performed by

means of the double ratio of isotope yields technique. Effects due to energy threshold in mass discrimination have been investigated. It has been observed that instrumental effects can play a significant role in the calculation of ratios involving isotopes with different Z values (He, Li), because of the strong dependence on Z of the energy losses in the material. The importance of this problem increases when the emitting sources are relatively slow and detectors are placed at large laboratory angles. Systematic errors of the order of 10% can be easily introduced in the T_{HeLi} temperatures, even for thin ΔE detectors (500-600 μm silicon equivalent).

The analysis here presented, together with those of ref. [21,28] indicates how it is possible to limit the effects of experimental identification thresholds by a careful study of the phase space and by applying eq. (1) to isotopes for which the phase space has been measured with similar efficiencies. In this respect it appears that using isotopes with the same Z value strongly reduces the effects induced by the energy threshold for discrimination.

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