IL NUOVO CIMENTO **45 C** (2022) 52
DOI 10.1393/ncc/i2022-22052-5

COLLOQUIA: IWM-EC 2021

Isospin influence on the thermal characteristics in the reactions $^{78,86}Kr + ^{40,48}Ca$ at 10 AMeV

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received 12 May 2022

Summary. — In this work, the preliminary results of the data analysis on the influence of the isospin on the thermometric characteristics, in the reactions $^{78}Kr+^{40}Ca$ and $^{86}Kr+^{48}Ca$ at 10 AMeV, will be shown. The thermal evaporation from compound nucleus and from the Quasi-Projectile have been studied within the thermometric method, based on the kinematic approach, in which the temperatures are extracted from the slope of the alpha particles energy spectra. Moreover, the values of the temperature, in fusion reactions, were measured with two different helium isotope ratio thermometers. In fusion-reactions higher temperature has been found for the system with higher neutron enrichment, independently of the nature of the method used for the determination of the temperature. This trend is confirmed by the comparison with the GEMINI++ statistical model. In contrast, for the Quasi-Projectile the observed temperature is lower for the neutron rich system. These results suggest that temperature is sensitive to the N/Z ratio.

1. – Introduction

Heavy Ion Collisions allow the study of nuclear matter under particular conditions of temperature and pressure, providing very important information about its characteristics. The isospin degree of freedom, namely the neutron-proton asymmetry, $\frac{N-Z}{A}$ can actually strongly influence these properties. In fact, some works in literature [1, 2], in which

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different temperature probes, both chemical and kinetic, were used, show a dependence of the thermodynamic quantities on the neutron enrichment. In order to look for the different behaviour, it is necessary to investigate reactions with different N/Z ratio.

In this work, the results of a study on the isospin influence on the temperature in the reactions ^{78}Kr+^{40}Ca and ^{86}Kr+^{48}Ca at 10 AMeV will be presented. Because of the very different neutron enrichment, from this moment, we will refer to the system ^{78}Kr + ^{40}Ca as the neutron poor system and to the ^{86}Kr + ^{48}Ca as the neutron rich system. The two studied reactions were realized in the context of the ISODEC experiment [3-6], which was carried out at INFN-Laboratori Nazionali del Sud, by using the high capabilities of the 4π multidetector CHIMERA [7, 8].

Thanks to the large difference in the N/Z ratio of the combination of projectiles and targets, the ISODEC experiment allows investigating the dependence on the neutron-proton asymmetry, of the competition among different reaction mechanisms and of nuclear properties; in our previous works it was observed that the cross sections of Fusion-Evaporation and Fusion-Fission strongly depend on the isospin [4] as well as the nature, a dynamic or statistic one, of the splitting of the Quasi-Projectile [9, 10].

Now, we have investigated the isospin influence on the temperature of the Quasi-Projectile and of fused system.

In order to measure the nuclear temperature, two different thermometric methods have been used, in particular the slope thermometer with the alpha particle as a probe and the double isotope yields ratio, often referred to as the Albergo thermometer [11]. Moreover, the results have been compared to the theoretical predictions of the GEMINI++ statistical model.

2. – Temperature in fusion reactions

The introduction of the concept of nuclear temperature is due to Weisskopf [12], who proposed a thermometric method for the determination of the temperature, consisting in the analysis of the kinetic energy spectra of light particles (neutrons, protons and alpha particles) emitted by an equilibrated source. The evaporation is a statistical process and thus the expected shape of the energy spectra is the one of the Maxwell-Boltzmann distribution, where the slope parameter is the temperature.

In order to strictly select the events due to the evaporation of the compound nucleus, in our analysis, we have taken into account only alpha particles, detected in coincidence with evaporation residues, namely the heavy fragments forward emitted (polar angle smaller than 15 degrees) and with the atomic number greater than 46 (Z of compound nucleus is 56).

As the temperature is extracted from the slope of the energy spectra, a good energy calibration of the detectors is necessary. The α particles, which are the probe that we are using, mainly release the most of their energy in CsI (Tl) scintillators, thus we have developed a special method, based on the time of flight, for the calibration of these detectors. For details, please see reference [13]. The alpha particles, selected in the way previously explained, exhibit energy spectra in the center of mass frame, independent of the emission angle and peaked around the same value, as expected in the case of production by an equilibrated emitting source and thus confirming the statistical character of the emission process. As the energy of the entrance channel (10 AMeV) is low enough to consider negligible the pre-equilibrium emission, we have used this kinetic method, by fitting the exponential slope of the energy spectra with just one moving source.

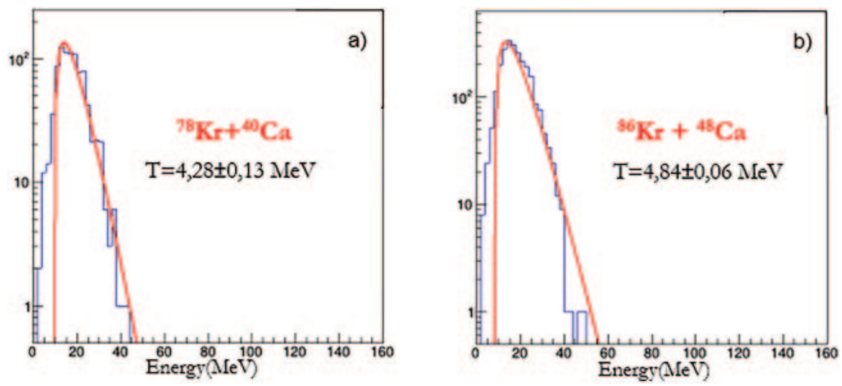

Fig. 1. – Energy spectra of alpha particles, emitted in coincidence with Evaporation Residues and fitted with a Maxwellian (red line), in panel (a) for the neutron poor system and in panel (b) for the neutron rich one.

It is possible to observe the results of the fitting procedure in fig. 1, where the alpha energy spectra are shown in the center of mass frame, at the laboratory angle of 20 degrees and where the red line represents the Maxwell fitting function, in panel (a) for the ^{78}Kr + ^{40}Ca system and in panel (b) for the ^{86}Kr + ^{48}Ca one. It should be noted that the experimentally extracted values of the temperature are not the temperatures of the initial nucleus but those of the evaporation residues, thus it is a kind of average temperature, because multiple alpha emissions can occur, subtracting progressively energy to the system and lowering its temperature. The values obtained for these temperatures are: 4.28 ± 0.13 MeV for the neutron poor system and 4.84 ± 0.06 MeV for neutron rich system, thus the temperature is higher for the system with a larger number of neutrons.

The obtained values of the temperatures are in agreement with other experimental results available in literature, indeed, they follow the trend of the composite caloric curve, temperature as function of the excitation energy per nucleon, for the nuclear mass number region 100–140, constructed by Natowitz and shown in panel (c) of fig. 4 in ref. [14]. The energy spectra of the alpha particles have been compared to the one reconstructed, with the same selection method used for the experimental data, by using the statistical model GEMINI++ (fig. 2). The entrance parameters of the code are the same used in the analysis on the influence of the isospin on the competition among Fusion-Fission and Fusion-Evaporation, described in ref. [4]. In particular, A/7 as the level density parameter and Jmax $= 73\hbar$ and Jmax $= 90\hbar$ as the maximum angular momentum, were used for the neutron poor system and for the neutron rich one respectively.

One can observe that even if the values of temperature, obtained with GEMINI++, are lower than those experimentally extracted, the behaviour is the same, providing a higher temperature for the neutron rich system.

The values of the temperature of the two studied systems have been extracted also with a chemical approach, by using the double isotope ratio thermometer, even if not all the conditions for the application of this method are fully satisfied. The double ratio is defined as

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

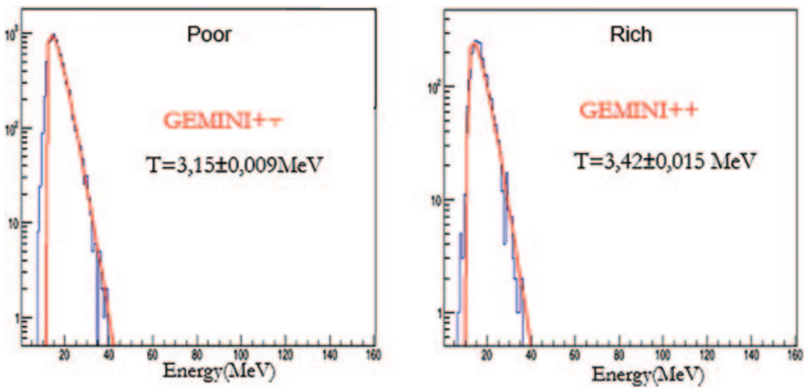

Fig. 2. – Energy spectra of alpha particles, with the same selection used for the experimental data, simulated with the GEMINI++ code and fitted with a Maxwellian (red line), for the neutron poor system (left) and for the neutron rich one (right).

where A_i and Z_i are the mass number and the atomic number of the considered isotopes. In order to avoid the Coulomb barriers influence, ΔA is chosen equal to 1 and $\Delta Z = 0$, moreover, these differences are the same for both the numerator and denominator for cancelling the neutron and proton chemical potentials effects. It should be observed that the temperature experimentally measured is an "apparent" temperature, because the sequential decays affect the equilibrium values of the isotope ratios. In literature, many works were conducted in order to define a correction factor k to quantify these secondary effects [15-17]. By indicating with B the binding energy, the relation between the apparent temperature T_{app} and the equilibrium value of the temperature T_0 is given by

$$\frac{1}{T_0} = \frac{1}{T_{app}} + \frac{\ln k}{B}$$

In our analysis we have measured the temperature by using helium isotope thermometers, thanks to the copious production of ^{3}He and ^{4}He. Because of the different neutron-proton balance, the neutron rich system prefers to produce heaviest nuclei of the same element respect to the neutron poor one, and so it is really hard to find common isotopes and consequently to use the same thermometers for both studied systems.

For the other pair of isotopes in the ratio, we have looked at the isotopic distribution of the lightest elements produced, lithium, beryllium and boron, shown in fig. 3 in red for the reaction ^{86}Kr + ^{48}Ca and in black for the other system ^{78}Kr + ^{40}Ca. We have chosen the isotopes produced in both the reactions, which are ^{6,7}Li and ^{9,10}Be. The temperatures, corrected from the distortions due to the secondary decays, with the factor semiempirically measured in ref. [15], are reported in table I.

It seems there is a small discrepancy between the two different isotope ratio thermometers; the temperature obtained with ^{6,7}Li/^{3,4}He is slightly higher than the one from ^{9,10}Be/^{3,4}He, perhaps the used correction factor is not sufficient to remove the fluctuations in the apparent temperatures. Even if the temperature is lower than the one obtained with the kinetic thermometer, the same behaviour is observed, with the neutron rich system showing a temperature higher than the neutron poor one.

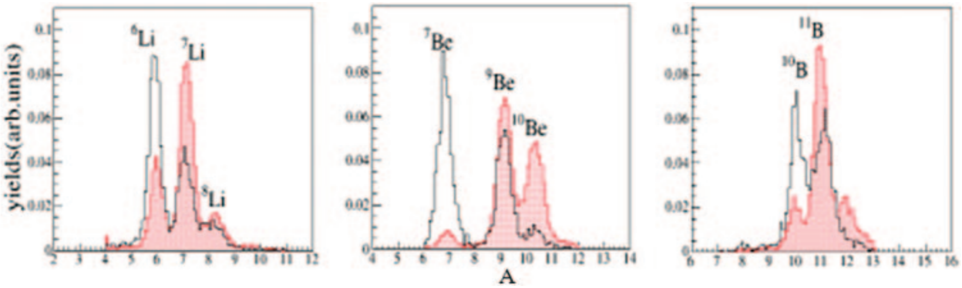

Fig. 3. – Isotopic distribution of lithium, beryllium and boron, in red for the reaction ^{86}Kr + ^{48}Ca and in black for ^{78}Kr + ^{40}Ca.

TABLE I. – *Temperatures obtained with the double isotope thermometers, $^{6,7}Li/^{3,4}He$ and $^{9,10}Be/^{3,4}He$.*

Isotope ratio	Temperature (MeV) ^{78}Kr+^{40}Ca	Temperature (MeV) ^{86}Kr+^{48}Ca
^{6,7}Li/^{3,4}He	2,64±0,06	2,72±0,06
^{9,10}Be/^{3,4}He	2,51±0,12	2,66±0,08

Also in this case we have compared the experimental results to the theoretical prediction of GEMINI++, but we could just use the thermometer ^{6,7}Li/^{3,4}He, because in the simulation the ^{10}Be isotope is produced with too low statistics to be used in the calculation. The temperatures obtained with the GEMINI++ code, reported in table II, are slightly higher than those experimentally extracted. While in agreement with the experimental results, the value of the temperature is higher in the system with highest neutron enrichment and this effect is more pronounced in the simulation.

TABLE II. – *Temperatures experimentally obtained from the $^{6,7}Li/^{3,4}He$ thermometer compared to those predicted by the GEMINI++ code*

Isotope ratio	Temperature (MeV) ^{86}Kr+^{48}Ca	Temperature (MeV) GEMINI++
^{6,7}Li/^{3,4}He	2,72±0,06	2,92±0,12

Isotope ratio	Temperature (MeV) ^{78}Kr+^{40}Ca	Temperature (MeV) GEMINI++
^{6,7}Li/^{3,4}He	2,64±0,06	2,76±0,12

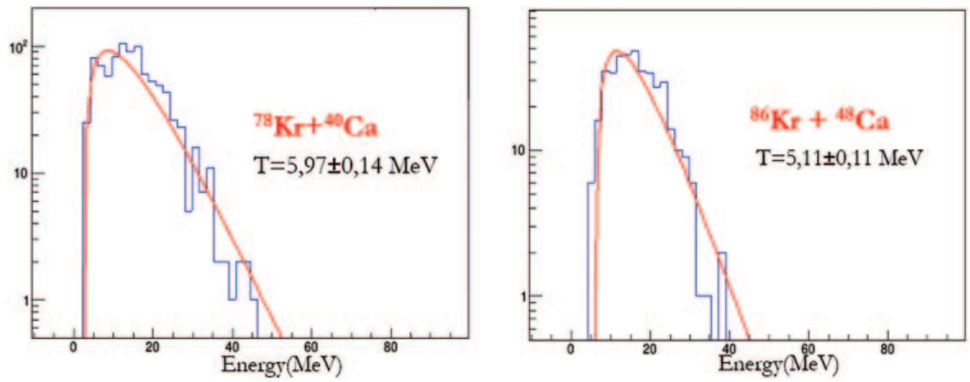

Fig. 4. – Energy spectra of alpha particles, emitted in the evaporation of the projectile fitted with a Maxwellian (red line), for the neutron poor system (left) and for the neutron rich one (right).

3. – Temperature of the Quasi-Projectile

The dependence of the temperature of the Quasi-Projectile on the isospin degree of freedom was also studied. We have taken into account only events in which v_{rel}, the relative velocity between the alpha particle and its heaviest partner in the evaporation of the Quasi-Projectile, satisfies the condition

$$0.6 \leq \frac{v_{rel}}{v_{Viola}} \leq 1.4$$

This requirement, together with the imposition of the condition of the completeness of events, should exclude fragments originating from the Quasi-Target. We had not considered the pre-equilibrium emission, because, as noted previously, this component is negligible at these energies.

The temperature is extracted from the slope of the energy spectra of alpha particles; the Maxwellian fit is represented by the red line in fig. 4. In agreement with other cases in literature [1, 2], higher temperatures have been obtained for the neutron poor system, that is in contrast to what was observed for fusion reactions.

4. – Conclusions

Very preliminary results of a study about the influence of the isospin on the temperatures in Fusion reactions and of the Quasi-Projectile have been presented for the ^{86}Kr + ^{48}Ca and for ^{78}Kr + ^{40}Ca collisions at 10 AMeV. Different approaches, a kinetic and a chemical one, have been applied: the values of the temperature have been extracted from the slope of the energy spectra of alpha particles and have been measured with two different isotope ratio thermometers. The results, independently of the nature of the used thermometer approaches, have put in evidence that for the evaporation residues from the compound nucleus the temperatures are higher for the neutron rich system, while lower temperatures have been found for the Quasi-Projectile with the highest neutron enrichment. A comparison of the experimental results, relative to the fusion reactions, with the GEMINI++ statistical model, confirms the isospin observed effect.

For the future we plan to improve the method used for the selection of events in which the Quasi-Projectile evaporation is observed. Moreover, the temperature of the Quasi-Projectile will be determined with another kinetic thermometer approach, by using the Momentum Quadrupole Fluctuations (MQF) method, based on the momentum of the emitted particles.

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