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

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Abstract. An investigation of the influence of the isospin (N/Z ratio) on the thermometric characteristics, in the reactions ^{78}Kr+^{40}Ca and ^{86}Kr+^{48}Ca at 10 AMeV is presented. The experiment was performed at the INFN Laboratori Nazionali del Sud in Catania by using the beams delivered by the Superconductive Cyclotron and the 4π multidetector CHIMERA. The isospin effects on the decay modes of the two produced composite systems and on the competition between statistical and dynamical break-up of the projectile have been studied. The thermal evaporation from both compound nucleus (CN) and Quasi-Projectile Like Fragment (PLF) has been investigated by extracting the temperature with two different thermometric methods, namely the slope thermometer, with the alpha particles as probe, and the double isotope yields ratio thermometer. The results of the analysis suggest the influence of the N/Z ratio on the system (CN or PLF) temperature, regardless of the nature of the method used for its determination.

1 Introduction

Nuclear matter characteristics and properties can strongly depend on the isospin degree of freedom, namely on the balance between neutrons and protons in the system, thus it is important to study heavy ion collisions that lead to similar systems with different ratio N/Z and look for the different behaviour. With this aim, the two reactions, ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca at 10 AMeV were realized at INFN - Laboratori Nazionali del Sud in Catania, by using the 4π multidetector CHIMERA. In fact, they lead to the formation of two composite systems that differ overall for sixteen neutrons and for this reason we refer to them as neutron poor (^{78}Kr + ^{40}Ca) and neutron rich (^{86}Kr + ^{48}Ca) systems. These reactions have been widely studied and the differences in the decay mechanism of the composite system [1,2,3] and in the competition between the statistic and dynamic break-up of the quasi-projectile [4,5] as a function of the neutron enrichment has been highlighted. In this work, the results relative to the investigation on the influence of the isospin on the temperature of the composite system and the quasi projectile by using two different approaches will be presented. Looking at the evaporated particles, it is possible to extract important information on the characteristic parameters of the emitter system, such as level density and temperature, which could change as a function of the neutron enrichment. We have measured the temperatures with two different approaches, a kinetic one in which the temperature is extracted from the slope of the energy spectra of the light particles evaporated [6] and a chemical one where the so called "Albergo thermometer" [7] has been used.

2 Experimental details

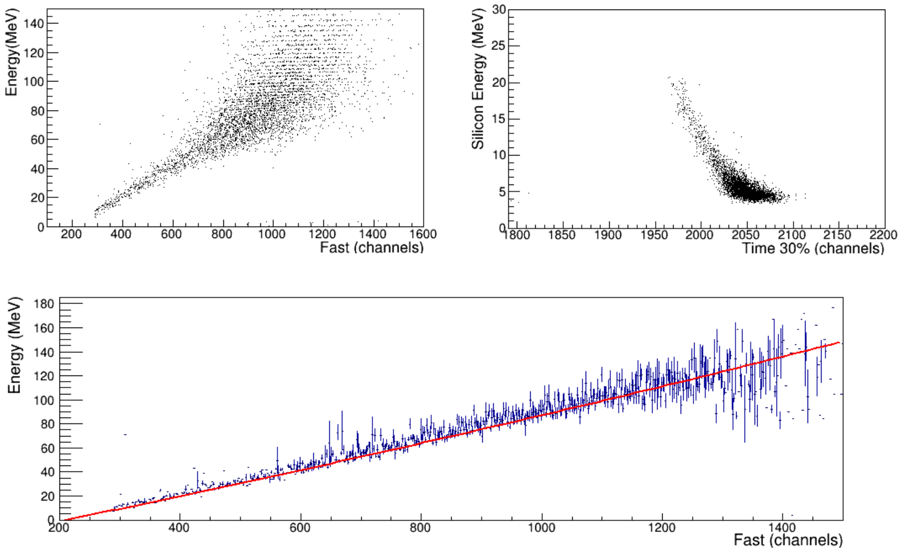

Fig. 1. Top left the residual energy, in MeV, calculated as explained in the text, plotted as function of the fast component of the light output response of the CsI(Tl) scintillator, photodiode readout, for the particles lying in the ΔE-ToF plot, panel on the right. In the bottom panel, a second degree polynomial, the red line, used as the fitting function of the experimental points in the profile diagram corresponding to the residual energy versus fast plot.

In this work the results relative to the ISODEC experiment will be discussed. The ISODEC experiment was realized in order to study the isospin influence on the competition among the different reaction mechanisms at low energy, by analysing the data collected for the reactions ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca at 10 AMeV. The experiment was performed at INFN-Laboratori Nazionali del Sud, in Catania, by using the 4π multidetector CHIMERA and the high quality beams, delivered by the Superconductive Cyclotron. The CHIMERA device [8] was crucial in the experiment allowing the precise measurements of key observables for the previous and current analysis, such as cross sections, charge and angular distributions, energy spectra, multiplicities and velocities. This multidetector is composed of 1192 telescopes, where the first stage is a silicon detector and the second one is a CsI (Tl) scintillator, coupled to a photodiode for the light reading. Four identification techniques [9] are available, ΔE-E, time of flight, pulse shape discrimination in the silicon detector and pulse shape analysis in the scintillator. In this analysis, for the application of the kinetic method, where the temperature is extracted from the energy spectra, a good energy calibration of the CsI(Tl) detectors is necessary. In fact, the α particles, the probe which has been used, have sufficient energy to punch through the silicon detector and mainly release most of their energy in the second stage of the telescopes, the scintillator. We have developed a special procedure, based on the time of flight technique, to perform the calibration of the CsI(Tl) detectors. The first step of the procedure is the selection of the α particles punching through the silicon, by using the ΔE-E technique. The total energy is obtained from the velocity as ½ Mv^2. The velocity is directly measured through the ToF method. In the calculation of the time of flight a fundamental step is the determination of the constant which takes into account all the effects affecting the time response of the reaction products, the t_0. The determination of t_0 is really complicated, especially for the particles stopped in the silicon detector and it requires a special procedure, well described in reference [10]. The residual energy, deposited in the CsI(Tl) scintillator, is obtained by subtracting to the total energy E the energy loss in the silicon detector, ΔE. Top left panel of Fig.1 shows the residual energy, in MeV, plotted as function of the fast component of the light output response of the CsI(Tl) scintillator, for the particles lying in the ΔE-ToF plot of top right panel of Figure 1. The calibration procedure is completed by using a second degree polynomial, the red line in bottom panel, as the fitting function of the experimental points in the profile diagram corresponding to the residual energy versus fast plot.

3 Experimental results

3.1 Isospin influence on the temperature of the composite system

To measure the temperature of the composite systems, formed in fusion reactions, we have used two different thermometric methods.
In the first one, based on a chemical approach, the values of the temperature of an equilibrated source, from which light fragments are emitted, have been evaluated by using the double isotope ratio thermometer, namely the “Albergo Thermometer”.

The double ratio is defined as: $R = \frac{Y(A_i,Z_i)/Y(A_i+\Delta A,Z_i+\Delta Z)}{Y(A_j,Z_j)/Y(A_j+\Delta A,Z_j+\Delta Z)}$ (1)

Where Y(Ai,Zi) and Y(Aj,Zj) are the yields of the selected isotopes, A_i and Z_i are the mass number and the atomic number of the considered fragments. In our analysis we have chosen fragments with ΔA =1 and ΔZ = 0, to avoid the Coulomb barriers influence. To cancel the neutron and proton chemical potentials effects, these differences are chosen the same for both the numerator and denominator. A serious inaccuracy in the determination of the temperature is caused by the sequential decays of the highly excited fragments produced in reactions at freeze-out, that affect the measured isotope yields. The experimentally measured temperature is therefore called “apparent temperature”, while the temperature before the sequential decays is called “real (source) temperature”. An empirical correction factor *k* [11, 12, 13] to consider the sequential decay effects was calculated by different authors in literature, for several isotope ratios. The relation which links the apparent temperature T_{app} to the equilibrium value of the temperature T_0 is given by: $\frac{1}{T_0} = \frac{1}{T_{app}} + \frac{lnk}{B}$ (2) where *B* is the binding energy. The temperature was extracted with helium isotope thermometers thanks to the copious production of ^{3}He and ^{4}He. To have a better comparison we have used the same thermometers by choosing couple of isotopes common to the two systems. Actually this is really difficult, because the neutron enrichment of the isotopes of the light elements produced reflects the one of the initial system, thus lightest isotopes of the same element are produced in the neutron poor reaction (^{78}Kr + ^{40}Ca) with respect to the neutron rich (^{86}Kr + ^{48}Ca) one. For this reason, the other pair of isotopes in the ratio, are ^{6,7}Li and ^{9,10}Be. In table 1 are tabulated the values of the “real temperature” obtained, by correcting the experimental "apparent temperature" with the factor *k* semiempirically measured in reference [11]. This factor seems to be insufficient to remove the fluctuations, in fact the temperatures evaluated with the two thermometers ($^{6,7}Li/^{3,4}He$ and $^{9,10}Be/^{3,4}He$) are slightly different, however they show the same behaviour, in both cases the temperature is higher for the neutron rich system. We have simulated the two studied reactions with the statistical code GEMINI++ and reported the values of the temperature theoretically predicted by using the $^{6,7}Li/^{3,4}He$ thermometer in table 2. It was not possible to use the $^{9,10}Be/^{3,4}He$ thermometer because of the insufficient statistic with which the isotope ^{10}Be is produced in the simulation. According to the GEMINI++ model the temperatures are higher for the neutron rich system compared to the neutron poor one, in agreement with what was observed experimentally.

Table 1. Temperatures experimentally extracted with the double ratio thermometer.

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

Table 2. Values of the temperatures experimentally extracted and predicted by the GEMINI++ model by using the double ratio thermometer.

Isotope Ratio	**Temperature (MeV) Experiment ^{78}Kr + ^{40}Ca**	**Temperature (MeV) GEMINI++ ^{78}Kr + ^{40}Ca**	**Temperature (MeV) Experiment ^{86}Kr + ^{48}Ca**	**Temperature (MeV) GEMINI++ ^{86}Kr + ^{48}Ca**
$^{6,7}Li/^{3,4}He$	2,64±0,06	2,76±0,12	2,72±0,06	2,92±0,12

The second thermometer used for the determination of the temperature is based on the kinetic approach. The temperature is evaluated by fitting the exponential slope of the energy spectra of the light particles emitted from an equilibrated source, with a Maxwell-Boltzmann function. In Fig. 2 the energy spectra of the alpha particles, chosen as probe, in the centre of mass reference frame, with the Maxwell-Boltzmann fitting function (red line), are shown in panel a) for the neutron poor system and in panel b) for the neutron rich one. These energy spectra are the convolution of the contributions of the different de-excitation steps in the decay of a highly excited nucleus, thus the temperature varies in time and its value experimentally measured is an apparent temperature. In agreement with the behaviour previously observed for the "Albergo thermometers", it seems that the neutron enrichment of the source influences the value of the temperature, in fact also in this case we have obtained lower temperatures for the neutron poor system. This behaviour is confirmed by the simulation performed with the GEMINI++ code. In the reference [14], Natowitz has collected data from several experiments constructing caloric curves, that are the temperature as function of the excitation energy, for different regions of nuclear mass. To include our experimental points, obtained with the slope thermometer, in the caloric curve relative to the region of mass number 100-140, we have calculated the excitation energy from the kinematics, by assuming a complete fusion as confirmed, for both systems, by the velocity spectra of the evaporation residues that are peaked around the compound nucleus velocity. As one can observe in Fig. 3 the values of the temperatures for both systems (blue point for the neutron rich system, red point for the neutron poor one) follow the trend of the corresponding caloric curve of the systematic of Natowitz for the region of mass of interest. Although the same behaviour of the temperatures was observed as a function of neutron enrichment, the values extracted for each system with the two different approaches (chemical and kinetic) are quite different in agreement with other cases in literature [17]. In any case, as previously highlighted the temperature measured with the slope thermometer is an apparent temperature while the one obtained by using the Albergo method is corrected for the secondary effects and this could explain the observed differences.

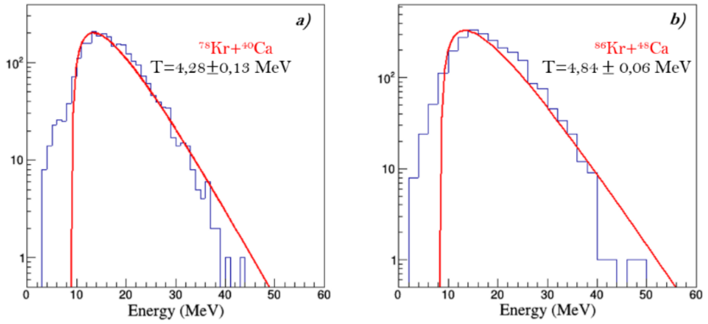

Fig. 2. Energy spectra of the alpha particles, evaporated from the composite system, in the centre of mass reference frame, with the Maxwell-Boltzmann fitting function (red line), in panel a) for the neutron poor system and in panel b) for the neutron rich.

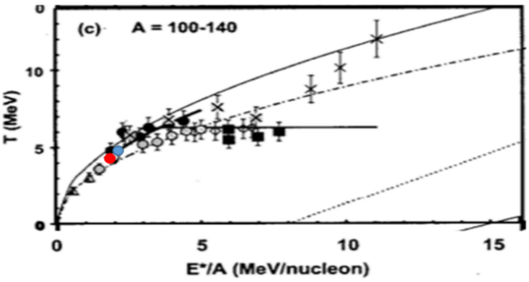

Fig. 3. Values of the temperatures for both systems (blue point for the neutron rich system, red point for the neutron poor one) in the corresponding caloric curve of the systematic of Natowitz for the region of mass of interest [14].

3.2 Isospin influence on the temperature of the Quasi-Projectile

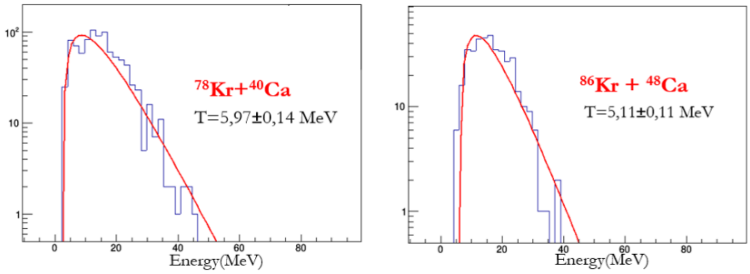

Fig. 4. Energy spectra of the alpha particles, evaporated from the Quasi- Projectile, in the centre of mass reference frame, with the Maxwell-Boltzmann fitting function (red line), on the left for the neutron poor system and on the right for the neutron rich.

The kinetic method was also used to extract the temperature of the Quasi- Projectile, also in this case we have used alpha particles as probe. Besides, to select just the fragments coming from the Quasi-Projectile and thus to exclude those originating from the Quasi-Target, we have imposed the event completeness and that the ratio between the relative energy between the alpha particle and its heavier partner in the evaporation of the Quasi-Projectile and the Viola velocity is included between 0.6 and 1.4. In contrast with the results obtained for fusion reactions, the temperature is higher for the neutron poor system, and this is in agreement with other cases in literature [15,16].

4 Conclusions

Results of the study of the isospin influence on the temperature of the composite systems formed in fusion reactions and in the alpha evaporation of the Quasi-Projectile, for the reactions ^{78}Kr+^{40}Ca and ^{86}Kr+^{48}Ca, have been presented. For the calculation of the temperatures of the composite systems from fusion, two different approaches, kinetic and chemical, were used and higher values of the temperature were observed for the neutron rich system compared to neutron poor one. The slope thermometer was used also for the extraction of the temperature of the Quasi-Projectile. In contrast to what was observed for the fusion reactions, but in agreement with other cases in literature, higher temperatures are evaluated for the neutron poor system.

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