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Isospin dependence of the nuclear temperature in the reactions ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca at 10 AMeV

Brunilde Gnoffo [a,b,*], Sara Pirrone [b], Giuseppe Politi [a,b], Enrico De Filippo [b], Giuseppe Cardella [b], Elena Geraci [a,b,c], Concettina Maiolino [d], Nunzia Simona Martorana [b], Angelo Pagano [b], Emanuele Vincenzo Pagano [d], Massimo Papa [b], Fabio Risitano [e,b], Francesca Rizzo [a,d,c], Paolo Russotto [d], Marina Trimarchi [e,b], Cristina Zagami [a,d,c]

[a] *Dipartimento di Fisica e Astronomia "Ettore Majorana", Universita degli Studi di Catania, via Santa Sofia 64, Catania, 95123, Italy*
[b] *INFN Sezione di Catania, via Santa Sofia 64, Catania, 95123, Italy*
[c] *CSFNSM-Centro Siciliano di Fisica Nucleare e Struttura della Materia, via Santa Sofia 64, Catania, 95123, Italy*
[d] *INFN Laboratori Nazionali del Sud, via Santa Sofia 62, Catania, 95123, Italy*
[e] *Dipartimento di Scienze Matematiche e Informatiche Scienze Fisiche e Scienze della Terra Universita degli Studi di Messina, Viale Ferdinando Stagno d'Alcontres, 31, Messina, 98166, Italy*

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ABSTRACT

The isospin dependence of temperatures is investigated in the reactions ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca at 10 AMeV. These reactions were studied in the context of the ISODEC experiment, performed at INFN-Laboratori Nazionali del Sud in Catania, by using the 4π multidetector CHIMERA. The results of the data analysis suggest that the temperature depends on the N/Z ratio. Different thermometric methods,as well as the slope and fluctuations thermometer with the alpha particles as probe and the double isotope yields ratio thermometer are used to extract the temperature of compound nucleus. Higher values of the temperature were observed for the neutron rich system compared to neutron poor one. This trend is confirmed by the comparison with the GEMINI++ statistical model.

1. Introduction

Nuclear temperature is a concept very important particularly in heavy-ion collisions where nuclei are brought to extreme energy conditions, forming a hot, dense system. Temperatures can be measured by using methods based on various approaches, including both kinematic and chemical techniques. One of such kinematic method is the slope thermometer, which estimates temperature based on the energy distribution of the light particles (neutrons, protons, and alpha particles) emitted from an equilibrated source, assuming they follow a Maxwell-Boltzmann distribution [1]. Another kinematic method involves the quadrupole fluctuation thermometer, which is based on analysing the fluctuations in the quadrupole moment of particle distributions [2,3]. In this work for both thermometers alpha particles were chosen as probe. One based chemical thermometer is the Albergo one [4], named after its proposer, relies on the ratio of isotope yields (e.g., helium and hydrogen isotopes) to determine nuclear temperature. This method assumes thermal and chemical equilibrium within the system, allowing to use isotope abundance to estimate the temperature. These

* Corresponding author.
E-mail address: brunilde.gnoffo@ct.infn.it (B. Gnoffo).

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Table 1
Experimental and simulated temperatures derived from $^{6,7}Li/^{3,4}He$ and $^{9,10}Be/^{3,4}He$ thermometers.

Double isotope yields ratio Temperature (MeV)				
Istope Ratio	^{78}**Kr** + ^{40}**Ca**		^{86}**Kr** + ^{48}**Ca**	
	Experiment	**GEMINI++**	**Experiment**	**GEMINI++**
$^{6,7}Li/^{3,4}He$	2.64±0.06	2.76±0.12	2.72±0.06	2.92±0.12
$^{9,10}Be/^{3,4}He$	2.51±0.12		2.66±0.08	

thermometers are essential in studying nuclear matter at extreme conditions, helping exploring the properties of matter under high temperatures and densities.

The isospin asymmetry (i.e., the ratio of neutrons to protons) is expected to impact the thermodynamic properties of nuclear matter, including temperature [5–7]. This work presents a study on the influence of isospin on the temperature of composite systems formed in fusion reactions, as determined by the thermometers previously described. In fact, the studied reactions $^{78}Kr+^{40}Ca$ and $^{86}Kr+^{48}Ca$ at 10 AMeV lead to the formation of two isotopes of Barium with a large difference in the N/Z ratio.

2. Experimental results

The $^{78}Kr+^{40}Ca$ (neutron poor system) and $^{86}Kr+^{48}Ca$ (neutron rich system) at 10 AMeV [8–12] were studied at INFN-Laboratori Nazionali del Sud in Catania, by using the multidetector CHIMERA [13,14], a powerful 4π array for charge and mass identification of reaction products with low energy threshold. At INFN-LNS, we also benefited from the high-quality beams provided by the Superconducting Cyclotron, which offered both the intensity and timing precision required for the experiment.

In order to avoid entrance channel effects due to peripheral collisions that could affect the results, we applied an experimental selection to the analysed events. To focus exclusively on nearly-central collisions, the thermometric methods were applied only by using fragments emitted in coincidence with evaporation residues, i.e. nuclei with Z>46 and velocities close to that of the compound nucleus.

2.1. Double isotope yields ratio temperatures

The Albergo thermometer, as already mentioned, can be used to estimate the temperature of an equilibrated nuclear source by analysing the ratios of isotopic yields. It relies on the principle that light nuclear fragments, emitted from an equilibrated source, as for example the compound nucleus, follow a statistical distribution. The temperature can be inferred by comparing the yields of specific isotopes that differ by one neutron ($\Delta A = 1$) but have the same proton number ($\Delta Z = 0$). By carefully selecting the isotopes in this way, the method minimizes the influence of factors like Coulomb barriers and chemical potentials, focusing on the thermal properties of the source. The double isotope ratio R is defined as:

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

where $Y(A_i,Z_i)$,$Y(A_j,Z_j)$ represents the yield of the isotope with mass number A and proton number Z. However, the measured temperature is considered an "apparent temperature," influenced by sequential decays of highly excited fragments. To correct for this, an empirical factor is applied to obtain the "real temperature."

In this work, due to the abundant production observed for ^{3}He and ^{4}He, helium isotope thermometers, were used to extract the temperature of the compound nuclei. To improve the comparison between the two systems, the same thermometers were employed by selecting isotopic pairs common to both systems, specifically ^{6}Li and ^{7}Li, and ^{9}Be and ^{10}Be. Additionally, the temperatures were determined, through simulations performed using the GEMINI++ code. A c++ version [15] of the original code [16] was employed in this work. All calculations were performed using the same input parameters as those reported in Ref. [9]. The maximum angular momentum values considered were $73\hbar$ and $90\hbar$, while a constant value A/7 was adopted for the level density parameter. The GEMINI++ code is based on a statistical model, reproducing the statistical decay of an excited nuclear system.

In the simulations, the temperature was measured by using only the $^{6,7}Li$ thermometer, as ^{10}Be was produced with statistics too low to be used in the calculations.

Table 1 shows the values of the real temperature, obtained by correcting the experimental apparent temperature using the factor k, which was semi-empirically measured as described in references [17–19] . While this correction factor mitigates fluctuations, it appears insufficient to fully eliminate them. This is evident as the temperatures derived from the two thermometers ($^{6,7}Li/^{3,4}He$ and $^{9,10}Be/^{3,4}He$) differ slightly. Nonetheless, both show the same trend: the temperature is higher for the neutron-rich system in both cases.This trend is confirmed in the temperature extracted by the yields obtained in the simulation performed with GEMINI++ code, also reported in Table 1.

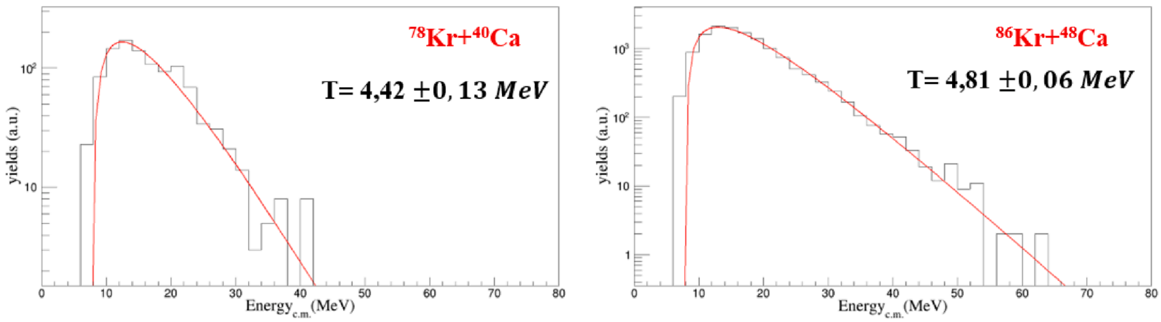

Fig. 1. The energy spectra of alpha particles,enitted by the compound nuclei, fitted with a Maxwell-Boltzmann distribution (red line).In the left ^{78}Kr + ^{40}Ca ^{78}Kr + ^{40}Ca and in the right ^{86}Kr + ^{48}Ca. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

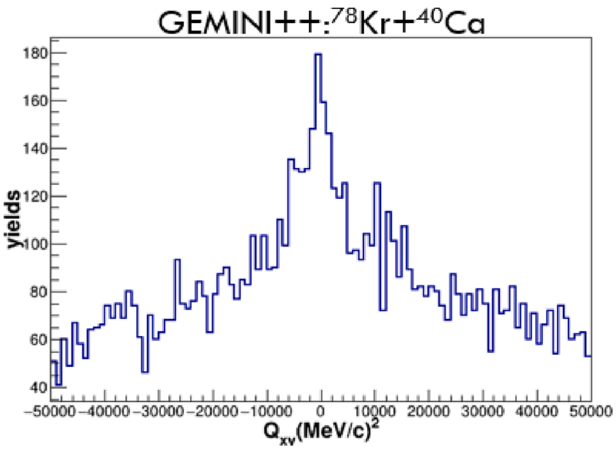

Fig. 2. Distribution of the transverse quadrupole momentum of the alpha particles simulated with GEMINI+ + code for the reaction ^{78}Kr + ^{40}Ca.

2.2. Temperatures extracted with kinematic approaches

The slope thermometer is a method used to determine the temperature of a system from the slope of the exponential decay in the energy spectrum. This technique is often applied in studies of fusion evaporation processes, where particles emitted by a compound nucleus can provide insight into the thermal properties of the system. In this work, the temperature of the compound nuclei were extracted with this method, by analysing the energy spectra of emitted alpha particles, fitting it with a Maxwell-Boltzmann distribution, as shown in Fig. 1. Panel (a) presents the spectrum for ^{78}Kr + ^{40}Ca system, while panel (b) illustrates the ^{86}Kr + ^{48}Ca system. The selection of alpha particles emitted by the compound nucleus was carried out by imposing coincidence with the evaporation residues with an atomic number greater than 46. The energy spectra are a result of the combined contributions from various de-excitation stages during the decay of a highly excited nucleus, as the temperature changes over time. Therefore, the experimentally measured temperature is actually an apparent temperature. Similar to the findings from the Albergo thermometers, it appears that neutron enrichment affects the temperature, with the neutron-poor system displaying lower temperatures compared to the neutron rich one. This behaviour is further confirmed by simulations performed with the GEMINI+ + code.

Another kinematic thermometer is the one based on the fluctuations of the quadrupole moment of the particles in the center-of-mass frame of the emission source. Specifically, assuming a Maxwell distribution of the momentum yields, it is possible to link the variance of the distribution to the system's temperature. A larger variance reflects greater thermal agitation, allowing the temperature of the nuclear source to be estimated by analysing these fluctuations. In order to avoid any contribution from the collision dynamics, which predominantly manifests along the beam direction, it is convenient to perform this analysis in the transverse plane to isolate the thermal properties of the system. Fig. 2 shows the distribution of the transverse quadrupole momentum, $Q_{xy} = p_x^2 - p_y^2$, of the alpha particles simulated with GEMINI+ + code for the reaction ^{78}Kr + ^{40}Ca. The distribution is peaked around zero. The peak is mainly due to the contribution of the alphas emitted at small angles. During the ISODEC experiment, to avoid an excessively high rate, the first two rings of CHIMERA, which cover a polar angle between 1° and 4 °, were shielded with screens. Consequently, information related to these angles is not available. By imposing a cut on the angles, the distribution takes the shape shown in Fig. 3, where the quadrupole moment distributions are displayed for angles between 4.6° and 6.4° and between 20° and 22°. In the same figure, the distributions obtained for the same angles, simulated with GEMINI+ +, are also shown. The simulations confirm the behaviour

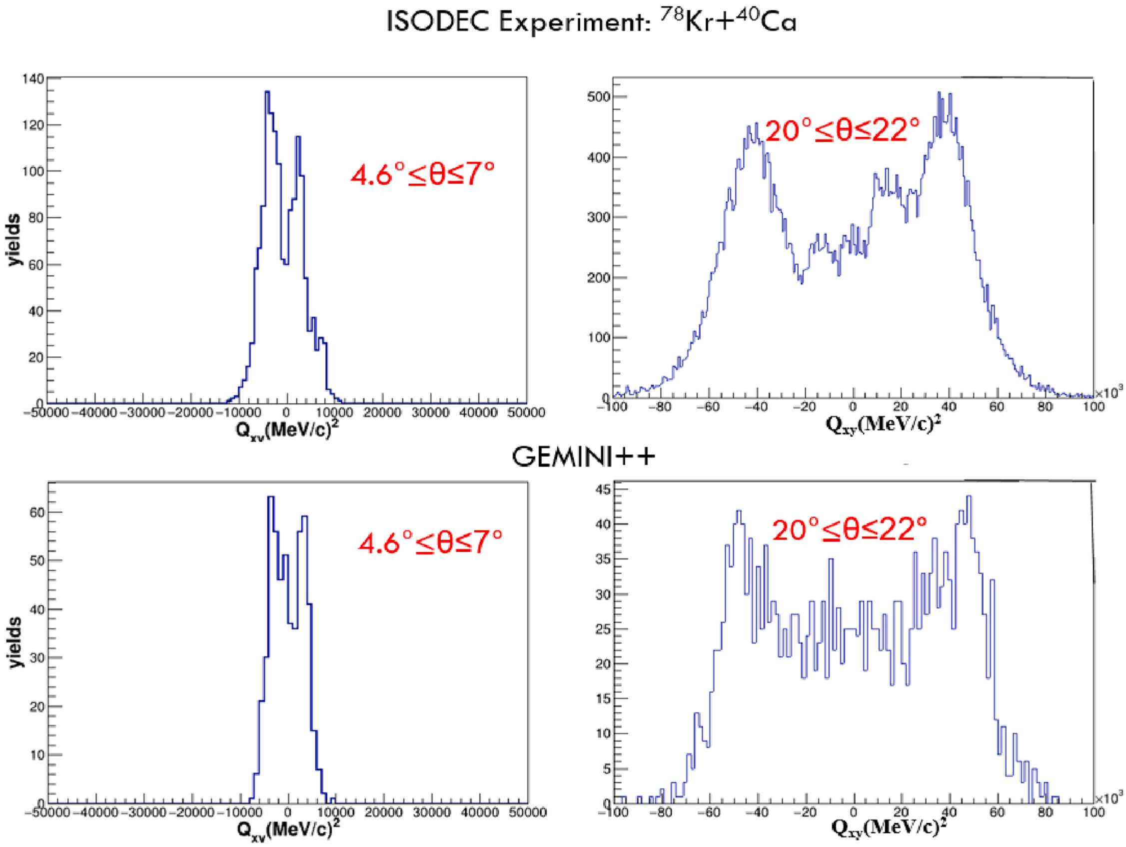

Fig. 3. Experimental (upper panels) and simulated (lower panels) quadrupole moment distributions for angles between 4.6° and 6.4° and between 20° and 22°.

observed experimentally. Since the peak at zero degrees can not to be observed for the experimental conditions, it is not possible to apply the method in a standard way. Therefore, studies are in progress to find a way to extract the temperature with this thermometer, taking into account the experimental limitations.

3. Conclusion

In this work, the study of the fusion reactions ^{78}Kr + ^{40}Ca and ^{86}Kr + ^{48}Ca at 10 AMeV is presented. This investigation seems to demonstrate the influence of isospin asymmetry on the temperature of compound nuclei. In fact, by using both the slope thermometer and the double isotope yield ratio method, the results show a correlation between the N/Z ratio and the extracted temperatures, with the ^{86}Kr + ^{48}Ca system exhibiting higher temperatures with respect to the other one. These findings, further supported by GEMINI + + simulations, highlight that isospin could play a critical role in understanding the thermodynamic properties of nuclear matter under extreme conditions. Studies are in progress to find a way to apply the thermometer based on the fluctuations on the distribution of the quadrupole momentum.

CRediT authorship contribution statement

Brunilde Gnoffo: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization; **Sara Pirrone:** Writing – review & editing, Investigation, Data curation, Conceptualization; **Giuseppe Politi:** Writing – review & editing, Investigation, Data curation, Conceptualization; **Enrico De Filippo:** Writing – review & editing, Software, Investigation, Data curation; **Giuseppe Cardella:** Writing – review & editing, Data curation; **Elena Geraci:** Writing – review & editing, Data curation; **Concettina Maiolino:** Writing – review & editing, Data curation; **Nunzia Simona Martorana:** Writing – review & editing, Data curation; **Angelo Pagano:** Writing – review & editing, Data curation; **Emanuele Vincenzo Pagano:** Writing – review & editing, Data curation; **Massimo Papa:** Writing – review & editing, Data curation; **Fabio Risitano:** Writing – review & editing, Data curation; **Francesca Rizzo:** Writing – review & editing, Data curation; **Paolo Russotto:** Writing – review & editing, Data curation; **Marina Trimarchi:** Writing – review & editing, Data curation; **Cristina Zagami:** Writing – review & editing, Data curation.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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