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**EFFECTIVE TEMPERATURES IN COMPLETE FUSION FOR
THE SYSTEM $^{58}\text{Ni}+^{58}\text{Ni}$ AT 500 MeV BOMBARDING ENERGY**

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Triple coincidences between complex fragments with $Z \geq 3$, light charged particles and γ transitions have been measured for the system $^{58}\text{Ni}+^{58}\text{Ni}$ at 500 MeV incident energy. To this end the HILI detector and a 19 pack BaF_2 cluster made of 19 crystals of TAPS geometry have been used. Effective temperatures have been obtained from the ratios of the bound excited level cross sections to the ground states ones for C, N and O evaporated after complete fusion of $^{58}\text{Ni} + ^{58}\text{Ni}$ at 500 MeV incident energy. The dependence of the effective temperature on the charged light particle multiplicity has been investigated.

1 Introduction

In the last few years growing attention has been paid to the emission of Complex Fragments (CF) from nuclear systems with high excitation energy and high angular momentum ^{1,2}. As often pointed out ³ there is an impressive variety of sources for CF spanning all kind of reaction mechanism: from peripheral interactions at almost any incident energy to the multifragmentation sitting in around few tens of MeV/nucleon. It has been shown ^{4,5,6} that CF become important and interesting deexcitation channels of equilibrated intermediate systems as soon as the excitation energy is of the order of hundreds

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Table 1: Parameters of the reaction studied in the present work (see text for details).

Proj.	Target	$E_{lab}(MeV)$	$E^*(MeV)$	$J_f(\hbar)$	$\sigma_f(mb)$	$J_g(\hbar)$	$\sigma_r(b)$
^{58}Ni	^{58}Ni	500	182	65	400	169	2.6

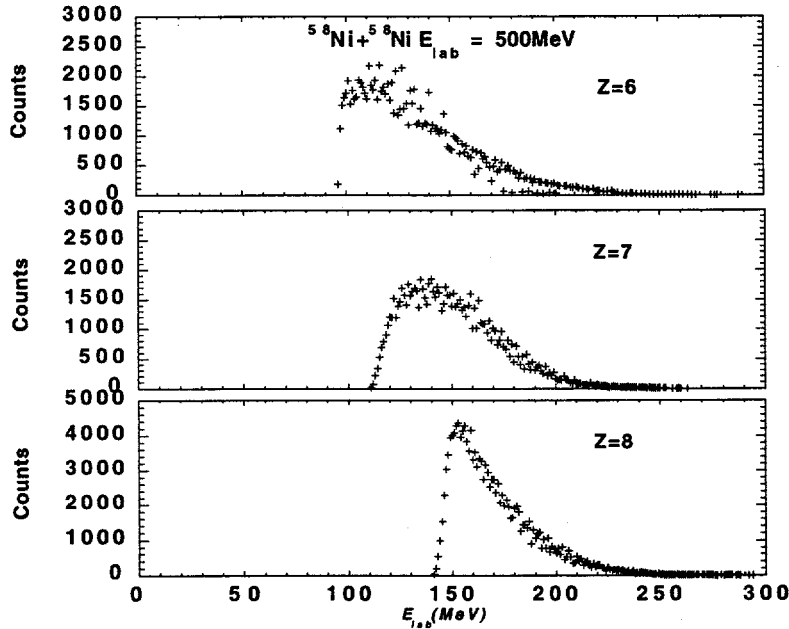


Figure 1: Energy spectra for Complex Fragments of $Z=6,7,8$.

of MeV, especially for the fusion cross section part corresponding to the highest angular momentum. Since the pioneering work of Stokstad et al.⁷ their emission has been interpreted in terms of statistical calculations based on the Hauser-Feshbach (HF) formulation. Besides the normal output channels including the evaporation of $p, d, t, ^3He, \alpha$ and γ up to 400 channels have been added. These extra channels consist of CF in their ground states, bound excited states and unbound and/or continuum excited states. From the ratio between the cross sections of couple of different levels of the same CF one can deduce the so called effective temperature⁸ that can be compared with the predictions of the statistical calculations and with the slope parameter deduced from the light particle energy spectra.

2 Experimental procedures

The experiment was carried out at the HHIRF of ORNL using a beam of ^{58}Ni accelerated by the 25MV Tandem alone. The machine was operated at a terminal voltage of 23.4MV and a charge state of 23+ was selected to get an analysed beam of 3enA average intensity. The HILI detector¹⁰ was used to detect charged particles. A 19 pack BaF_2 cluster, made up of crystals of TAPS¹¹ geometry was placed at 90° with respect to the beam direction to detect γ in the energy range 1-10MeV. A self-supporting target of ^{58}Ni 300 $\frac{\mu\text{g}}{\text{cm}^2}$ thick was used. A thick Ta disc 6cm diameter was placed coaxially with the beam at the entrance of HILI to reduce the counting rate due to the elastic scattering. In Table 1 are summarized the parameter of the reaction. E^* is the excitation energy of the intermediate system. J_f and σ_f are the critical angular momentum and cross section for complete fusion, respectively. J_c and σ_r are the grazing angular momentum and total reaction cross section, respectively, as deduced from current systematics. The master trigger for the acquisition was supplied by the signal coming from the large PPACs placed in front of the four quadrants of HILI. The time of flight signal between PPACs and BaF_2 crystals was used to discriminate the γ pulses against neutron pulses coming from the BaF_2 . Charged particle- γ coincidence events and charged particle singles events were detected.

3 Experimental results

The data were written in list mode on EXABYTE tapes. One and two dimension spectra were built off-line using the analysis package of the Physics Division of ORNL. The charged particle energy calibrations were performed using energy loss calculations based on the Ziegler systematics¹². The code ABSORB¹³ has been used to build the energy loss tables that were then used in the scan program to build the final energy spectra. The Fig. 1a-c shows the energy spectra for CF of $Z=6 \div 8$. The energy thresholds correspond to the energy lost in all the entrance windows of HILI.

The γ spectra shown in Fig. 2a-c represent the γ transitions emitted in coincidence with CF of $Z = 6, 7, 8$ respectively. The γ energies were corrected of the Doppler shift on an event by event basis, assuming a two body kinematics and using a mass of the CF corresponding to the minimum of the stability valley. In the γ spectra are clearly seen the peaks corresponding to the de-excitation of discrete states of $^{12,13}\text{C}$, ^{15}N and ^{16}O . The width of the peaks are coherent with the expected energy resolution of BaF_2 crystals ($\sim 10\%$ at 660keV). This finding shows that the Doppler correction was well taken into

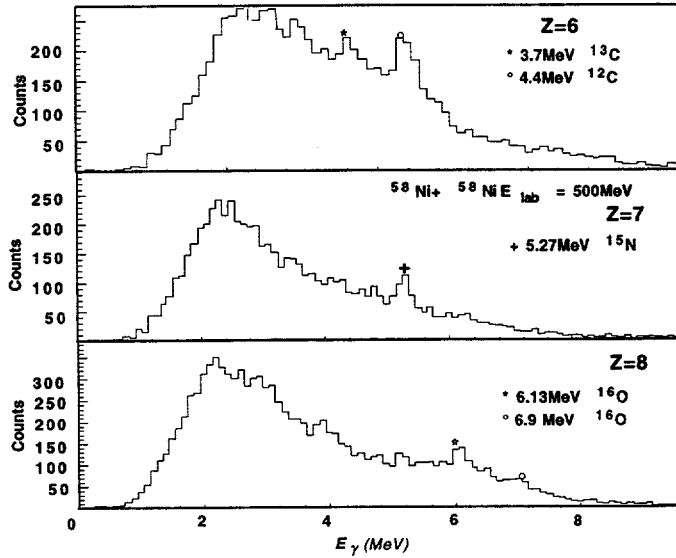


Figure 2: γ spectra detected in coincidence with Complex Fragments of $Z=6,7,8$ by means of a 19 pack BaF_2 cluster.

account. In Fig. 3a-b are reported the p and α spectra in coincidence with the Evaporation Residues (ER) as a function of the relative energy of the light particle with respect to the ER.

4 Effective temperatures and "slope" temperatures

The ratios between the cross sections of couples of states of the CF are often parametrized in terms of the energy gap, ΔE , between the two levels, their spins, S_1 and S_2 , and the parameter T_{eff} , the effective temperature, in the following way⁸ $\frac{\sigma_1}{\sigma_2} = \frac{2S_1+1}{2S_2+1} \exp\left(-\frac{\Delta E}{T_{eff}}\right)$. T_{eff} could be regarded as the temperature of the emitting source in the approximation of a one step emission from an equilibrated source with zero angular momentum and excitation energy E^* much higher than ΔE . In Table 2 are reported the T_{eff} deduced from couples of states in ^{12}C , ^{13}C , ^{15}N and ^{16}O , where the level at lower excitation energy is always the ground state. These results have been obtained taking into account the absolute efficiency of the BaF_2 cluster, measured with calibrated standard γ sources. The energy dependence of the efficiency response has been also checked by means of simulations performed with the computer code GEANT3. The level at 5.27 MeV in the ^{15}N is a doublet with spins of $\frac{1}{2}$ and $\frac{5}{2}\hbar$, this is

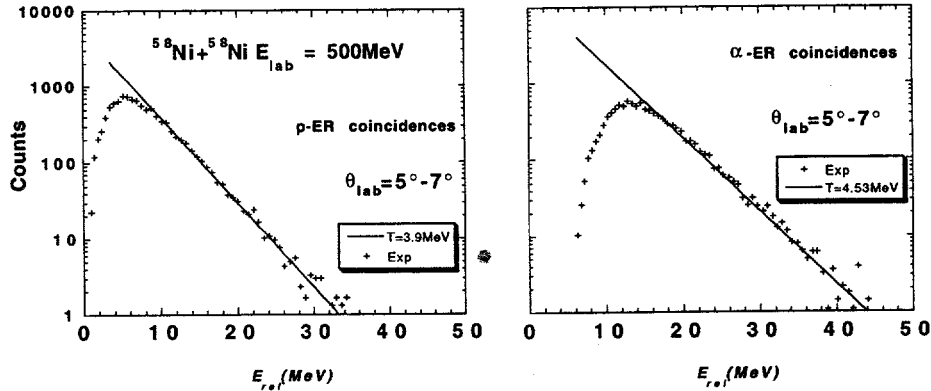


Figure 3: Spectra of p and α particles in coincidence with the ER as a function of the relative center-of-mass energy (E_{rel}). The solid lines are the results of an exponential fit with the indicated slope value T .

why there are two values for T_{eff} (see Discussion below). For each couples of levels we report two values for T_{eff} , one corresponding to CF- γ coincidences without any condition on the charged light particles (*noveto* column) the other corresponding to the experimental requirement that no charged light particles were detected by HILI at same time as the CF and the γ (*veto* column).

In Fig. 3a-b are reported the spectra of p and α detected in the angular bin $\theta_{lab} = 5^\circ \div 7^\circ$ in coincidence with the Evaporation Resisues (ER) as a function of the relative center-of-mass energy (E_{rel}). The procedure adopted to obtain these spectra is described and discussed in ref. ⁶ The high energy part of the spectra has been fitted with the expression $\exp\left(-\frac{E_{rel}}{T_{sl}}\right)$ to extract the slope parameter (T_{sl}) reported in the figure's legends.

5 Hauser-Feshbach calculations

Statistical calculations have been performed using the evaporation codes BUSCO⁵ and LILITA⁹. As pointed out elsewhere⁵ the peculiarity of BUSCO code is that it can handle the emission from the Compound Nucleus of nuclear species going from the neutrons to any CF in all the possible excitation states. The main limitations are that, being a code that calculatates cross sections analytically (not using Montecarlo methods, like LILITA e.g.) it calculates accurately the first step emission and in an approximate way multiple emissions. For the same reason one cannot get energy spectra and angular distributions in the laboratory reference frame. In order to follow the deexcitation of the primary

Table 2: Experimental Effective Temperatures obtained from the ratio of yields corresponding to excited states and to ground states of Complex Fragments (columns T_{eff}^{noveto} and T_{eff}^{veto}) and Effective Temperatures obtained from the ratio of cross sections calculated with BUSCO, corresponding to excited states and to ground states of Primary Complex Fragments (column T_{eff}^{pri}).

CF	E_{lev}^* (MeV)	$S(gs)$ (\hbar)	$S(E_{lev}^*)$ (\hbar)	T_{eff}^{noveto} (MeV)	T_{eff}^{veto} (MeV)	T_{eff}^{pri} (MeV)
^{12}C	4.44	0	2	$3.3 \pm .5$	$3.9 \pm .5$	3.8
^{13}C	3.70	0.5	1.5	$3.4 \pm .7$	$3.8 \pm .7$	3.7
^{15}N	5.27	0.5	2.5	$3.8 \pm .6$	$3.9 \pm .6$	3.7
^{15}N	5.27	0.5	0.5	19 ± 4	22 ± 5	
^{16}O	6.13	0	3	$2.5 \pm .7$	$2.9 \pm .7$	3.8
^{16}O	6.90	0	2	$2.1 \pm .8$	$2.3 \pm .8$	3.9

excited CF through light particle and γ emission and to build the energy spectra of the CF, the output of BUSCO is used as input to LILITA, selecting the appropriate option to handle a distribution of primary decaying nuclei. Besides all what has been mentioned so far, there are the "usual" degrees of freedom due to the choice of parametrizations and parameters for the transmission coefficients and level densities. In the calculations that we are commenting here we used the standard level density parameter of $a = \frac{A}{10}$ which gives a value for the compound nucleus temperatures based on the relation $T = \sqrt{\frac{E^*}{a}}$ of 3.9 MeV. In Table 2 are reported the effective temperatures deduced using the primary cross sections for C, N and O calculated by BUSCO (T_{eff}^{pri}).

6 Discussion

There are interesting comments to make concerning the experimental effective temperatures summarized in Table 2. For the ^{15}N case it is clear that in the present reaction the state at 5.27 MeV with spin $\frac{1}{2}$ is weakly or not at all populated. As a matter of fact, if the yield had to be attributed completely to this spin, one would get an unreasonable high value of T_{eff} (~ 18 MeV). On the contrary, if one assumes that only the spin $\frac{5}{2}$ is produced, a coherent value of T_{eff} is obtained. In this particular case the T_{eff} observable can help in assigning the spin of the CF excited states. The reason why two values of T_{eff} were obtained, with and without light charged particles associated with the CF, was qualitatively based on the fact that HILI covers a rather

small angular range around the beam direction ($\sim \pm 25^\circ$ both in θ and in ϕ). Noticing that charged light particles, like protons and α , can have two main sources, the Compound Nucleus (CN) and the primary CF with excitation energies above particle thresholds, with different velocities (CN is much slower than CF), it can be inferred that charged light particles emitted by CF are more forward peaked than the ones emitted by the CN. Then, requiring that HILI had detected a CF, but not light particles, would reduce selectively the statistics of CF, in the sense that CF that do not emit light particles (and then evaporated with excitation energy below the particle threshold) should be preferentially detected. As a result the vetoed T_{eff} should be more representative of the temperature of the CN^{4, 8}. What is indeed observed is that there are no significant differences between the T_{eff} with or without veto.

The absolute values for C and N are in a satisfactory agreement with the value of $T = 3.9 MeV$ deduced from the relation $T = \sqrt{\frac{E^*}{a}}$ with $a = \frac{A}{10}$. They are also in agreement with T_{eff}^{pri} deduced from BUSCO calculations shown in Table 2. On the contrary the experimental value of T_{eff} for $Z = 8$ is rather lower. From BUSCO calculations, that predict a maximum for $Z = 6$ in the CF yield¹⁴, it is seen that 60%, 50% and 40% of $Z = 6, 7$ and 8 , respectively, are evaporated at excitation energies below the particle threshold. Then higher the mass of the CF, lower will be that fraction, as expected from a thermal sharing of the available excitation energy. Since the particle decay of CF will preferentially populate ground states or low energy excited levels of secondary CF⁴, the effective temperature measured selecting CF with excitation energy below the particle threshold should be higher than the effective temperature measured without any selection. It seems that there is a disagreement between the predictions and the experimental results. It could also be that the qualitative argument on the selection criteria of primary CF is not quantitatively strong enough. More quantitative experimental analysis and more sophisticated calculations are presently underway.

It is interesting to consider the slope parameters reported in Fig. 3. That is a completely independent procedure to obtain an estimation of the nuclear temperature of the source of light particles. The agreement between these slope parameters and CN temperatures obtained from the relation $T = \sqrt{\frac{E^*}{a}}$ and from BUSCO calculations is a strong argument to confirm the Complete Fusion origin of the ER and associated light particles. Finally, if the T_{eff} deduced from the CF will be confirmed, we'll have an even more convincing argument to conclude that CF and light particles are emitted from a common equilibrated source, in the present case.

7 Summary and conclusions

In this paper we have presented experimental results and evaporation calculation concerning the system $^{58}\text{Ni} + ^{58}\text{Ni}$ at 500 MeV incident energy. It has been shown that emission of light particle from primary excited CF do not significantly affect the effective temperature deduced from the ratios between cross sections of excited states and ground states of CF with $Z = 6, 7, 8$, although statistical calculations show that, at this incident energy, 40 % of ^{12}C , 50 % of ^{15}N and 60 % of ^{16}O are evaporated at energies above the particle threshold. Certainly additional investigations are needed in order to assess this crucial point. It is very interesting that the temperatures values deduced from light particle energy spectrum slopes in coincidence with ER are coherent with the value obtained from the statistical calculation and with the effective temperatures deduced from the cross section ratios.

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