Statistical (?) decay of light hot nuclei

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This experiment is aimed at progressing in our understanding of the statistical properties of light nuclei at excitation energies above the particle emission thresholds.

Physics goals include the determination of the level density in the $A \sim 20$ region, the interplay between continuum and discrete particle-unstable states, as well as the exploration of possible α-clustering at high excitation energy for the two isotopes ^{21}Ne,^{20}Ne.

We propose to pursue this study by measuring light charged particles in coincidence with evaporation residues, identified in mass and charge, for the reaction $^{12}C +^{9} Be$ at 7.9 $A.MeV$. The experiment will be performed with the Ring-Counter [1], coupled to Garfield [2] (now fully equipped with digital electronics and with increased granularity and performances) with a nearly-4π coverage.

A back-tracing technique based on correlation functions of the relative kinetic energy of isotope pairs is proposed, in order to isolate the contribution of specific steps of the decay. The comparison of exclusive data with the prediction of the statistical model, which explicitly includes all the experimentally measured particle unstable levels for this mass region, will allow to make a step forward in this study.

We require 3 days of pulsed TANDEM ^{12}C with a beam current of about 0.1 pnA on target (III Hall).

INTRODUCTION

The statistical theory of compound nucleus decay is one of the oldest achievements of nuclear physics and has proved its remarkable predictive power since sixty years[3]. Within this theory the detailed output of a generic nuclear reaction is uniquely predicted under the knowledge of the inverse process probability and some specific nuclear properties, namely nuclear ground states properties and level densities.

Level densities represent fundamental quantities in nuclear physics. Their knowledge is not only important for the understanding of nuclear structure, but it is also required for different applications of nuclear physics, from nucleosynthesis calculations to reactor science. Their direct measurement from transfer reactions[4] has made impressive progress in the last years, but it is limited to a relatively low excitation energy domain. Above the thresholds for particle decay, level densities are only accessible in evaporation reactions through the theory of compound nucleus decay.

Despite the fundamental interest of the issue, only inclusive experiments have been used up to now to constrain this fundamental quantity[5], and very few studies exist altogether concerning the evaporation of very light nuclei in the mass region $A \sim 20$ [6–8]. This mass region is however very interesting to explore for different reasons:

- both theoretical and experimental studies[9] point to a limiting temperature increasing with decreasing compound mass; in this sense light nuclei are better suited to high temperature nuclear thermodynamics studies;
- hot light nuclei, in the mass region $A \sim 20$ and with excitation energies of the order of 3 MeV per nucleon, are massively produced in multifragmentation reactions; their statistical behaviour is thus essential to access the properties of heavy excited sources at break-up time[10];
- the domain of validity of the Hauser-Feshbach theory of statistical evaporation is not clear in this mass region. A different decay model, the so-called Fermi break-up, is known since a long time [11] and has been extensively used, but no unique experimental information exists on the transition, if any, between these two regimes;

- some excited states of different nuclei in this mass region are known to present pronounced cluster structures; these correlations may persist in the ground state along some selected isotopic chains[12]; according to the Ikeda diagrams[13] alpha-clustered excited states are massively expected at high excitation energies close to the multi-alpha decay threshold in all even-even $N = Z$ nuclei; such states should lead to exotic non-statistical decay which start to be identified in the recent literature[14].

These issues are clearly intercorrelated: a trustable modelization of highly correlated alpha-clustered states in the continuum is very difficult to achieve[15], however such effects might be experimentally seen as an excess of cluster production with respect to the prediction of the statistical model, provided that the ingredients of the latter are sufficiently constrained via experimental data.

The general concern with this kind of studies is that the final inclusive yields represent integrated contributions over the whole evaporation chain. Because of that, the information they bear on specific excitation energy regions of the different nuclei explored during the evaporation process may be model dependent[16]. A progress on these topics thus demands an exclusive and (quasi)complete detection of the different decay products emitted in fusion reactions. We propose a coincidence measurement of the residual nucleus, resolved in charge and mass, with its different emitted light charged particles, as well as a back-tracing technique based on correlation functions of the relative kinetic energy of isotope pairs, to isolate the contribution of specific steps of the decay.

THE LEVEL DENSITY OF LIGHT NUCLEI

Monte-Carlo shell model calculations[17] indicate that the simple non-correlated Bethe counting of fermionic states can precisely describe the many-body correlated level density of real nuclei, provided a backshift is introduced for pairing and the level density parameter $a(A, E^*)$ is propertly adjusted as a function of nuclear mass and excitation energy.

A complete systematics below the particle emission threshold covering the whole mass table[8] confirms this statement. In the case of ^{26}Al, a value $a = 2.90 MeV^{-1}$ and $\delta = -2.91 MeV$ produce an excellent fit of the complete level scheme at low excitation energies and s-wave neutron resonance spacings at the neutron binding energy. At higher excitation energy, experimental information can be extracted from particle spectra measured in fusion reactions. These data point to a level density parameter of $a = A/11$ for $A \sim 120$, which rapidly decreases with increasing excitation energy[18], and becomes a constant $a = A/8$ value for $A \sim 40$[19]. A recent analysis of inclusive spectra obtained in the reaction $^7Li +^6 Li$ at 14-20 MeV incident energy[7] has produced results which are still in agreement with the statistical model, if the level density parameter is increased to $a = A/4.5$ and deformation is included at high angular momentum[20]. These findings are also consistent with qualitative expectations from surface effects and excitation energy dependence of the effective mass[21].

On the other side, the low-energy information[8] can also be understood in terms of a Boltzmann-like functional form for the level density, the so-called constant temperature expression[22], which is currently used in some statistical models to account for the discrete part of the spectrum[23]. The extrapolation of the constant temperature parameters in the region $A \sim 20$ to energies above the particle emission threshold would lead to a very different functional form for the level density, which has not been tested in high excitation energy experiments. Therefore, the functional form of the level density above the threshold, as well as the value of the a parameter are still open to debate[24].

We have recently developed a Monte-Carlo Hauser-Feshbach code[25] which explicitly includes all the experimentally measured particle unstable levels from the online archive NUDAT2, covering an excitation energy region that can easily exceed 1 MeV per nucleon in the mass region $A \sim 20$, and it is therefore particularly suited to study the possible transition between the constant temperature and Bethe expression, as well as the relevance of the discrete part of the spectrum in the evaporation process.

On the other hand, the population of these particle-unstable excited states can be experimentally accessed via the correlation function technique. A detailed comparison of these populations to the predictions of the code will give direct information of the population yields at the last-but-one evaporation step in specific isolated decay chains. These yields in turn are expected to be directly connected to the functional form of the level density and/or to possible violations of statistical rules due to cluster structures in the continuum.

Comparison with other well-known statistical models (LILITA-N97, ABLA-07) through direct collaborations with the code owners[26] are also planned to further check the model independence of the results.

THE PROPOSED EXPERIMENT

To progress in the understanding of the statistical properties of highly excited light nuclei, our experimental strategy is based on different complementary observables. A coincident measurement of quasi-complete evaporation chains will be performed, in order to evidence possible contributions of non-statistical decay and get information on clustering in the continuum. Moreover, a reconstruction of the last-but-one evaporation step will be achieved through the direct measurement of excited states population with chosen correlation functions, in order to select the matching point between the discrete and the continuum part of the excitation spectrum and extract information on the level density. These observables will be associated with the more standard energy spectra of evaporated particles in coincidence with an evaporation residue.

The experiment will be performed with the Ring-Counter(RCo) [1], coupled to Garfield [2] with a nearly-4π coverage, now fully equipped with digital electronics [27]. This apparatus has the capability to measure the charge, the energy and the emission angles of nearly all the charged reaction products, allowing an excellent discrimination of the different reaction mechanisms. It also provides information on the mass of the emitted charged products in a wide range of particle energy and type. In particular the RCo detector has an isotopic resolution up to $Z = 9$, an angular coverage $5 \leq \theta \leq 18$, an angular resolution $\Delta\theta \approx 1$ and an energy resolution of silicon strips and new CsI(Tl) detectors given by 0.3% and 2-3%, respectively. These values, measured from laboratory tests, are suitable for correlation measurements. The identification of the charge of fragments stopped in the Silicon detector via pulse shape and digital electronics resulted feasible, as in previous tests at LNL of the FAZIA detectors. This possibility will allow also to lower mass identification energy thresholds.

To construct the observables of interest with the above mentioned apparatus we need a compound nucleus reaction fulfilling the following conditions:

- inverse kinematics or symmetric reactions, such that the evaporation residue overcomes the detection threshold and can be used to select the reaction mechanism;
- an initial compound excited in the continuum, to be sensitive to the level density;
- a final decay in the resonant part of the spectrum, to be reconstructed with correlation functions;
- final residues not exceeding $Z = 6 - 9$, to be identified both in mass and charge in the RCo.

According to our HF simulations, the ensemble of these requirements can be fulfilled by the reactions that could potentially be studied at the TANDEM, which are listed in table 1.

Reaction	E_{Beam} (MeV)	θ_{gr}	A_{CN}	Z_{CN}	v_{CN} (cm/ns)	E^*_{CN} (A.MeV)	σ (mb)
$^{12}C+\,^{9}Be$	95	3	21	10	2.2	2.8	400
$^{12}C+\,^{12}C$	95	4	24	12	2.0	2.6	430
$^{11}B+\,^{11}B$	70	4	22	10	1.8	2.7	450
$^{11}B+\,^{12}C$	87	4	23	11	1.9	2.8	460

TABLE I: List of possible reactions. The compound characteristics are evaluated through the systematics, based on measurements of linear momentum transfer. The compound formation cross sections are calculated with PACE4.

For this proposal we concentrate on the $^{12}C +^{9} Be$ reaction. The other proposed reactions lead to similar results. Figure 1 shows the probability distributions of the number of decay steps in the continuum and in the discrete for the decay of a ^{21}Ne nucleus at an excitation energy of 2.8 $A.MeV$, as predicted by our HF calculations.

In the most favorable case of a single decay step from the discrete part of the spectrum, which represents 60% of the simulated events, the reconstruction of the discrete level population via the correlation function between the residue and the last emitted particle gives a direct measurement of the population of the mother nucleus at the preceeding step in the continuum, that is the density of states.

This possibility can be inferred from figure 2 (upper part) showing the simulated effect of the variation of the physical inputs on the $^{12}C-p$ correlation function. In the standard version of the code a rigid body momentum of inertia for spherical nuclei is used for the calculation of the rotational energy, while in the calculation given by the red dashed line deformation effects are included following ref.[7]. We can see that the properties of the compound nucleus in the continuum, in this case the deformation, affect considerably the population of the discrete states, which can be recognized as the peaks in the correlation function. This behaviour makes the

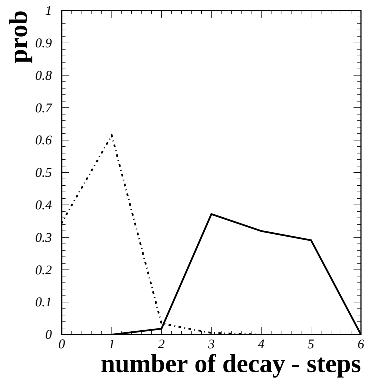

Fig. 1: HF calculation of the probability distribution for: the total number of decay steps (continuous curve); the number of decay steps occurring from a discrete state of a parent nucleus (dashed curve) in the decay of a ^{21}Ne nucleus at an excitation energy of 2.8 $A.MeV$.

correlation technique a powerful tool to study the level density of nuclei in the continuum, if complemented by other observables such as the energy spectra and the angular distributions in order to further constrain the model.

Coming to the investigation on alpha-clustering, we show in figure 2 (lower part) the effect of the level density on the predicted alpha yields. A mass dependent parametrization of a/A, leading to $a \approx A/5$ for $A \approx 20$, is used in the calculation given by the black line, while the level density parameter has been fixed to $a = A/8$ for the red line. According to our simulations, the form of these distributions do not depend on the number of the emitted neutrons. This suggests that the lack of neutrons detection does not represent a real limit to our purposes.

We can see that an important contribution of multiple alpha decays is observed even in standard HF, especially if a realistic parametrization of the level density parameter is used. In particular a high probability ($\approx 25\%$, corresponding to a measured cross section of about $4mb$) of a complete desintegration of Ne into 5 α is predicted by the model, and it is enhanced if the level density parameter follows the experimental systematics. The presence of alpha-clustering phenomena can be enlightened comparing the data with these model predictions.

REQUESTED BEAM TIME

We ask for pulsed ^{12}C TANDEM beam at 7.9 $A.MeV$, for a beam time of 3 days, which does not include the time needed for the Accelerator Staff to set the beam, energy and timing (about 1 ns resolution, 200 ns repetition period).

The required ^{12}C pulsed beam intensity is about 0.1 pnA, to minimize the dead time of the acquisition, with an estimated acquisition counting rate of $3MHz$. We will measure with ^{9}Be target with a thickness of 185 μg/cm^2. The target has to be as thin as possible to avoid energy straggling of emitted particles and the consequent worsening of the correlation functions.

Considering the following:

- a compound nucleus formation cross section of 400 mb;
- a beam intensity of 0.1 pnA;
- a target thickness of 185 μg/cm^2;
- an efficiency of about 20% of the device for the detection of the total charge of the compound nucleus (12% for the detection of all the charged products in events with a single decay from the discrete part of the spectrum), an amount of 1% of the events corresponding to a single decay of a resonant state of the type $^{13}N^* \rightarrow p +^{12} C$ at the end of the evaporation chain (this estimation was obtained filtering our HF predictions through a software replica of the apparatus);

we estimate that in 3 days of beam we should measure a number of isotope pairs sufficient to estimate primary isotopic yields from correlation functions (at least 1000000 $p -^{12} C$ pairs).

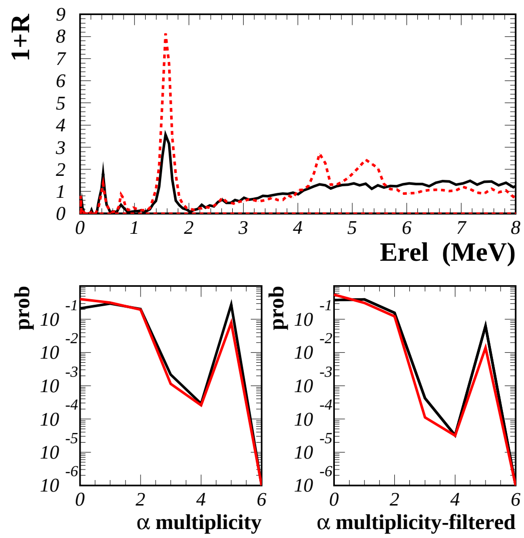

Fig. 2: Effect of the variation of the physical inputs of the HF model in the decay of a ^{21}Ne nucleus at an excitation energy of 2.8 $A.MeV$. Upper panel: $^{12}C-p$ correlation function obtained with the standard version of the code (black line) and when deformation effects included in the calculation of the moment of inertia, with parameters taken from[7] (red dashed line). Calculations are filtered through the experimental apparatus. Lower panel, left part: predicted alpha multiplicity distribution with the standard version of the code (always black line) and with a level density parameter fixed to $a = A/8$ (red continuous line). Right part: alpha multiplicity distribution after the filter for the apparatus, normalization to the number of events with a complete detection of the initial charge $Z = 10$, which are about the 20% of the simulated ones).

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