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Compound nuclear lifetimes at high excitation energies via a new statistical fluctuation method

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Abstract

A new method to determine compound nuclear lifetimes at high excitation energies is proposed and applied to the system $_{12}C(^{28}Si, \alpha)^{36}Ar$ at two different bombarding energies, 190 and 277 MeV. The alpha particle spectra show a structure which directly reflects the fluctuating behavior of the first de-excitation step. Coherence widths and thus lifetimes for the nucleus ^{36}Ar were obtained via a correlation function analysis. The results at low excitation energies are consistent with standard statistical models while the result at high excitation energy is compatible with a theoretically predicted change of the level density parameter.

Compound nuclear lifetimes are connected to statistical properties of nuclei and determine the time scale of statistical de-excitation in heavy ion collisions. Hence, they test the validity of the compound nucleus models at very high excitation energy where it is necessary to compare the various reaction times with the lifetime of a compound nucleus. For example, lifetimes for particle emission at high bombarding energies must be compared to the thermalization process and set the applicability limits for the statistical description of very hot nuclei formed in this type of nuclear reaction. Furthermore, level densities provide a test for nuclear models and their parameters.

Amongst the conventional methods of measurement of compound nuclear lifetimes we may cite the determination of the coherence width Γ [1] and the direct lifetime techniques by exploiting either atomic phenomena (the ''atomic clock'' [2], blocking effects [3]) or the intensity interferometry [4–6].

The atomic clock method is best suited for the study of lifetimes of last or near last chance decays of compound systems of high atomic number where the K-vacancy lifetime approaches the compound nuclear lifetime in the 10^{-16} to 10^{-17} time region. The crystal blocking technique too, is limited to the last disintegration step and may determine lifetimes in the region 10^{-16}s to 10^{-19}s. The intensity interferometry

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technique provides the spatio-temporal dimensions of the object. The separation of the two parameters, time and size of the object, is difficult and ambiguous in most cases.

The level width Γ is related to the lifetime via the uncertainty relation, $\Gamma \approx \hbar/\Delta t$. For low excitation energies, the states of the compound nucleus are narrow and widely spaced, $\Gamma \ll D$, where D is the mean spacing of the states. As the energy is varied the cross section is dominated by one resonance at a time (level counting method [1]). For high energies the compound nuclear levels overlap, $\Gamma \gg D$, and the cross section is no longer dominated by one level but has contributions from many nearby levels. According to the Ericson theory [7–9], the cross sections show large fluctuations due to interference effects between the overlapping resonances. Then the compound nucleus lifetimes can be accessed experimentally via correlation functions of excitation functions of reaction channels leading to a resolved final state or to a set of final states in a small excitation energy interval. However the determination of Γ and thus of the lifetime by this method has some fundamental shortcomings discussed in detail previously [10]. Alternatively in another method [10], the coherence width is obtained from the cross correlation on the final step energy spectra which are taken at different incident energies. This method is particularly suited for highly excited compound nuclei decaying by sequential particle emission. Then the simultaneous detection of two sequential particles allows the observation of discrete final states in the daughter nucleus and a correlation function analysis can be applied.

In the present work an attempt is made to present a more general method, which can be applied at much higher excitation energies, as long as the reaction process proceeds through a compound nucleus and sequential decay.

The principle of the method is illustrated in Fig. 1. As shown, the process has been reversed from the previous method, and for one incident energy a compound resonance is related to several states in the daughter nucleus through the emission of particles (e.g. alpha particles) at several energies. At high bombarding energies the daughter nucleus will be excited at energies E_2^* with widths, $\Gamma \gg D$. Hence Ericson fluctuations may appear and the energy spectrum of the emitted particles will show a particular structure which will directly reflect the behavior of the first de-excitation step.

In more detail from energy conservation we have

$$E_2^* = E_1^* - \varepsilon_1 + Q_1 \tag{1}$$

$$E_3^* = E_1^* - \varepsilon_1 - \varepsilon_2 + Q_1 + Q_2 \tag{2}$$

where E_1^*, E_2^*, E_3^* are the excitation energies of the first, second and third compound nucleus respectively, ε_1, ε_2 are the kinetic center of mass energies of the particles emitted in the two de-excitation steps (Fig. 1) and Q_1, Q_2 the corresponding Q-values. Hence the excitation energy of the nucleus resulting after one particle decay is completely determined, within the experimental energy resolution, by ε_1. The energy spectrum ε_1 will therefore reflect the Ericson fluctuations of the compound nucleus Y (Fig. 1).

It has to be pointed out here that the fluctuations in the emitted particle spectrum can be only observed if the excitation energy E_1^* is very well defined. This is a critical point for the application of the technique. In the

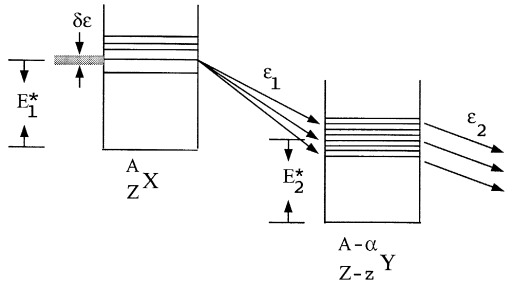

Fig. 1. Schematic illustration of the new proposed method, for a particle emitted of mass α and charge z.

present experiment the goal was to obtain E_1^* with very small uncertainty, less than $\delta\varepsilon \approx \Gamma_2/10$, where Γ_2 is the coherence width of the daughter nucleus. Once the effect is observed, this condition may be somewhat relaxed, with subsequent corrections due to the limited resolution [11]. In this way the compound nucleus is produced in a very narrow energy domain and can subsequently decay by emission of light particles with well defined energies bearing the same uncertainty $\delta\varepsilon$ as the one assigned to the compound nucleus excitation energy. These particles in turn will populate a narrow energy domain in the daughter nucleus. The interference of levels of this daughter nucleus will be manifested themselves through the fluctuations observed in the particle energy spectrum. The particles evaporated in the second decay step will present a smooth energy spectrum since they come from a mother nucleus excited in several overlapping states (Eq. (2)). More explicitly, the unobserved first particle of energy ε_1 introduces an integral over all energies $E_3^* - E_1^*$ satisfying Eq. (2), that will smoothen any structure. Moreover all other particles produced by other reaction mechanisms in the entrance channel will also present a broad energy spectrum. This fact is an important feature of the method: if a structure appears on the particle spectrum it is necessarily related to the first desexcitation step of a compound nucleus. All other particles will only give a smooth contribution to the spectrum. It proves simultaneously and without any ambiguity the formation of a compound nuclear system.

It is also possible with the proposed method, to determine the lifetimes of the first compound nucleus. For that it is necessary to vary the beam energy in very fine steps. The structures in the spectrum of the first particle emitted then fluctuate as a function of E_1^* and we can extract the correlation functions between spectra measured at different bombarding energies in the standard way.

To obtain an excitation energy E_1^* with a small uncertainty, $\delta\varepsilon \leq \Gamma/10$, the following conditions have to be fulfilled:

i) The beam energy resolution has to be of the order of $\delta\varepsilon$. This was possible in the present experiment with the beam analyzing alpha spectrometer at the GANIL-laboratory which can provide a resolution of the order of $\Delta E/E \sim 2 \times 10^{-4}$.

ii) The target has to be very thin to avoid an appreciable energy uncertainty due to energy loss in the target.

iii) A good resolution has to be achieved for the particle detection (energy resolution smaller than $\delta\varepsilon$). This was made possible by using the magnetic spectrometer SPEG of GANIL.

Additionally, in order to maximize the effect of the Ericson fluctuations on the spectra, the detection has to be performed at zero degrees and by using spin zero particles [1] to have the lowest possible number of statistically independent channels.

The method was tested by studying the reaction ^{12}C(^{28}Si, α)^{36}Ar, which proceeds via the compound nucleus ^{40}Ca. This nucleus decays to ^{36}Ar by evaporation of alpha particles. The coherence width Γ can be calculated by the following empirical formula [12]

$$\Gamma = 14 \cdot \exp\left(-4.69\sqrt{\frac{A}{E^*}} \right) \tag{3}$$

where A and E^* are the mass and excitation energy of the compound nucleus, and the resolution has to be of the order of 5×10^{-4} in order to satisfy the condition $\delta\varepsilon \leq \Gamma/10$.

A ^{28}Si beam was accelerated by the first cyclotron at GANIL and analyzed in the alpha spectrometer, the slit settings of which were chosen to give a relative energy resolution of 3×10^{-4}. A beam of 190 and 277 MeV impinged on a $20\,\mu$g/cm^2 ^{12}C target, located at the object point of the SPEG spectrometer. The evaporated alpha particles were detected at 0° in the focal plane of SPEG, which has a nominal resolution of 2×10^{-4}, and were identified by the energy loss measured in an ionization chamber and by the residual energy in a plastic scintillator. Since the detection was at 0°, special care had to be taken to stop the Si beam before the position measurement. For that a 75 μm kapton foil was used and magnetic rigidities were chosen to avoid beam charge states in the central region of the focal plane.

Energy spectra of α particles were observed in the following three different conditions. With a beam energy at 190 MeV, two measurements were performed by selecting different energy slices of the alpha spectrum by

different magnetic rigidities in SPEG, and a third one with an incident beam energy at 277 MeV, corresponding to another charge state of ^{28}Si at the same magnetic rigidity for the cyclotrons. A typical alpha spectrum is shown in Fig. 2, where small but clear structures are apparent. Detector effects such as differential nonlinearities may be excluded as origin of the structures by the fact that the period and the amplitude of the structures varies as experimental conditions are changed. The continuous line shown corresponds to a fourth order polynomial function which was used to reproduce the smooth part of the spectrum, $\langle\sigma(E)\rangle$. Subsequently, coherence widths were deduced from the analysis of such spectra, in the standard way, with the help of the auto-correlation function, using the following formula:

$$C_2 = \frac{\Gamma_2^2}{\Gamma_2^2 + dE_2^{*2}} = \frac{\langle\big(\sigma(E_\alpha + dE_2^*) - \langle\sigma(E_\alpha + dE_2^*)\rangle\big)\big(\sigma(E_\alpha) - \langle\sigma(E_\alpha)\rangle\big)\rangle}{\langle\sigma(E_\alpha + dE_2^*)\rangle\langle\sigma(E_\alpha)\rangle} \tag{4}$$

where $\sigma(E_\alpha)$ and $\sigma(E_\alpha + dE_2^*)$ is the cross section at E_α, $E_\alpha + dE_2^*$ respectively and $\langle\sigma(E_\alpha)\rangle$ and $\langle\sigma(E_\alpha + dE_2^*)\rangle$ the average cross section at E_α, $E_\alpha + dE_2^*$ which, as usual in fluctuation analysis, is energy dependent and is obtained from an averaging procedure of the data. A typical correlation function obtained in this way is shown in Fig. 3. A summary of the results together with other experimental details are presented in Table 1. The absolute value of the correlation function is of the order of 10^{-3} to 10^{-4}, corresponding to an effect of a few percent in the spectra. The lower value observed for higher α-particle energy may be due to a higher contribution of preequilibrium in this domain. A more systematic study of this absolute value may show the importance and, eventually, at high energies the disappearance of the compound nucleus formation. The present results are too limited in order to conclude on this subject.

In Fig. 4 the present experimental widths are shown and are compared with the systematic behavior of other experimental values found in a previous compilation [13] and Ref. [11]. In the same figure the observed widths

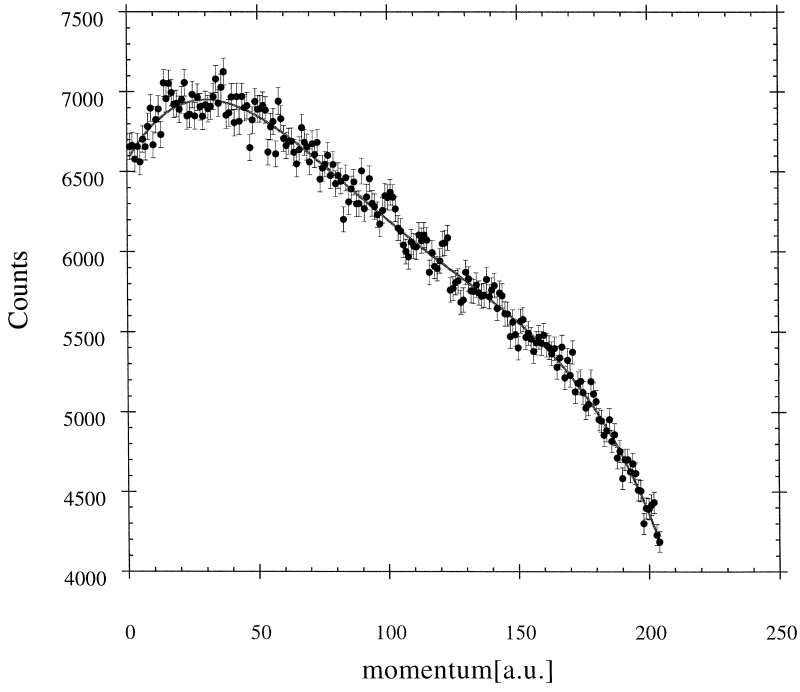

Fig. 2. A typical alpha spectrum obtained with SPEG at 0°, at a bombarding energy $E = 277$ MeV.

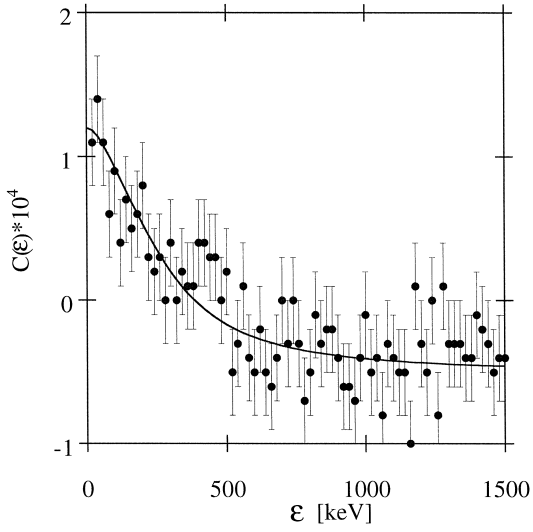

Fig. 3. Correlation function obtained with the alpha spectrum shown in Fig. 2 and Eq. (3), see text.

are compared with statistical model calculations, using the code CASCADE [14]. The calculations were performed for level density parameters $\alpha = A/8$ and $A/10$ MeV^{-1}. Moreover, since the empirical relation of Eq. (3) implies a straight line in this plot, a linear fit to the data contained in the compilation of Ref. [13], excluding the present results, is shown too.

The CASCADE calculation reproduces well the slope of this line and agrees within a factor of two with a level density parameter $\alpha = A/8$. This factor two is probably due to the fact that CASCADE does not contain explicitly shell structure effects in the level densities. Indeed, the gross features of the experimental data for $(A/E^*)^{1/2} \geq 1.1$ were nicely reproduced in [13] with a microscopic theory which includes the nuclear pairing interaction. For the first time we make use of data that gives the level width of a nucleus for a broad region of excitation energy, i.e. $0.8 \leq (A/E^*)^{1/2} \leq 1.4$. The value at the excitation energy $E_2^* = 59.8$ MeV, $(A/E^*)^{1/2} = 0.8$, corresponds to a completely unexplored region. For $\alpha = A/8$, it corresponds to a temperature of $T = 3.7$ MeV. Most models predict in this temperature domain a transition of the level density parameter from $\alpha = A/8$ to $\alpha = A/13$ [15,16].

In summary, it has been shown, using a new experimental method, that compound nucleus lifetimes can be determined up to very high excitation energies as long as the reaction proceeds through a compound nucleus system. This is why the method can be used, at least in principle, to sign the disappearance of compound nucleus formation. Our result at high excitation energy indicates a deviation from the $A/8$ value of the density parameter but obviously the high excitation energy regime $A/13$ predicted is not reached in the present experiment. The new experimental method proposed and used to obtain unambiguously the coherence width of

Table 1
Correlation function amplitudes, coherence widths and lifetimes for ^{36}Ar at different beam and α particle energies corresponding to the excitation energies E^* in ^{36}Ar

E_{beam} (MeV)	E_α (MeV)	E^* (MeV)	$C(0)\times 10^{-4}$	$\Gamma_{\rm CM}$ (KeV)	$\tau(10^{-21}$ s)
190	48.3	38.7	25 ± 5	60 ± 12	6.6 ± 1.3
190	59.0	32.7	2^{+2}_{-1}	51 ± 25	7.5 ± 3.8
277	69.4	59.8	1.7 ± 0.4	240 ± 40	1.6 ± 0.2

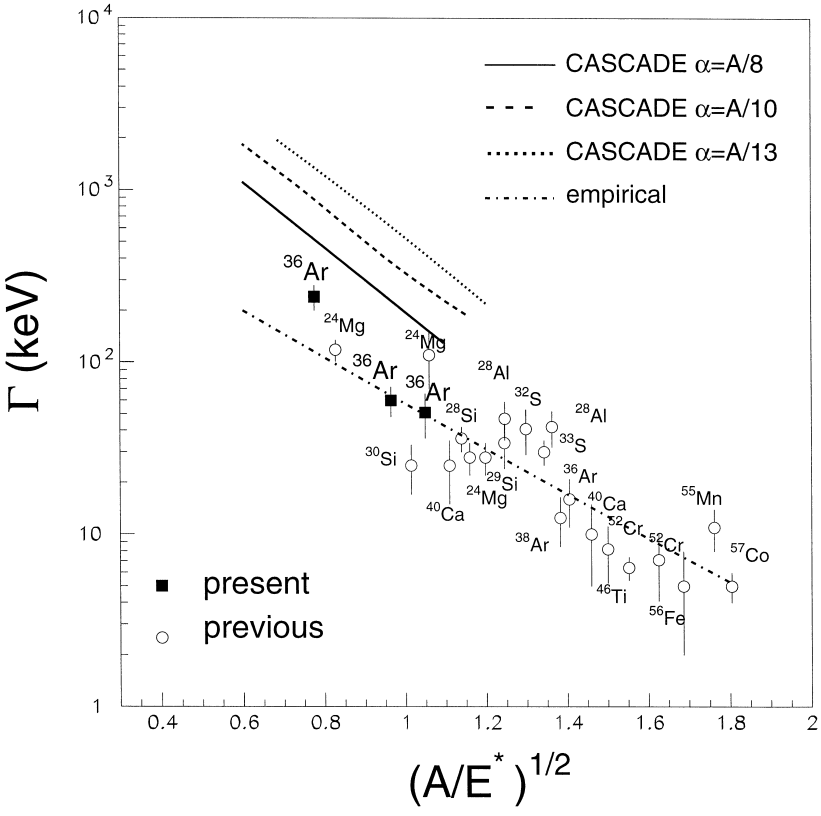

Fig. 4. Presently determined widths are compared with the compiled values [11,13]. The dotted line represents a linear fit to the compiled data. Statistical CASCADE calculations with different density parameters are shown, too.

compound nuclei at high excitation energies gives a new insight into the physics of high excitation energy nuclear dynamics.

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