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Alpha particle emission from the ^{198}Pb compound nucleus: comparison between the fusion-evaporation and the pre-scission channels

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Abstract. The α-particle emission from the ^{28}Si+^{170}Er fusion-evaporation reaction at 165 and 185 MeV has been measured and compared with published data relative to the pre-scission emission in the same reaction. The spectra in the two channels exhibit nearly the same shape in the low energy region, whereas in the high energy region the spectrum for the fusion-evaporation case features a larger apparent temperature. The interpretation of the difference in shape between the two decay channels is based on statistical model calculations which account for the effects due to the different length of the decay chain. Statistical model calculations with standard parameters describe well the gross features of the alpha particle spectra in the fusion-evaporation channel and the proton spectra in the pre-scission channel. On the contrary, the model predictions seem to overestimate by $\simeq$2 MeV the emission barrier for the alpha particles in the pre-fission channel. This effect is ascribed to the larger elongation of the nucleus during the fission process. An average axis ratio b/a$\sim$2 for the emitter is suggested.

PACS. 25.70.Gh Compound nucleus – 25.70.Jj Fusion and fusion-fission reactions

1 Introduction

It is well known that the experimental pre-scission multiplicities of charged particles [1-4], neutrons [5] and γ-rays [6] emitted in the fission process at high excitation energy cannot be quantitatively accounted for by the standard statistical model (SM). This effect has been interpreted as an evidence of evaporation during the dynamical evolution of the fissioning system from the equilibrium to the scission configuration. Experimental pre-scission multiplicities have been used to extract quantitative estimates of the dynamical fission time τ_f, a quantity which is strongly related to the the magnitude of the nuclear viscosity. The inclusion of a fission delay in SM calculations results in a much better reproduction of the experimental multiplicities. A further improvement of the model calculations has been achieved by using the measured kinetic energy of the pre-scission neutrons as an additional constraint [7].

Dynamical models have been successfully employed to describe the time evolution of the fission process [8,9]. However, they are not able to reproduce simultaneously the average energies and the multiplicities of the pre-scission α particles [10,11]. This failure still occurs after the inclusion of a refined treatment of the dependence on the deformation of the level density, the emission barrier and the binding energy [11].

In the modelling of the pre-scission emission, it is often assumed that SM calculations which use standard values of the level density parameter, emission barrier and binding energy describe correctly the statistical decay of the compound nucleus in the fusion-evaporation channel. Those standard values are then substantially modified to take into account the elongation of the fissioning nucleus in the pre-scission channel. In particular, the emission barrier is of crucial importance in the case of α particles. In fact, it has long been known that even small variation of the emission barrier induces substantial changes on the multiplicity and on the energy distributions of the α particles [12]. On the other hand, it has to be noted that the need of empirical adjustments of the emission barriers to describe correctly the experimental data has been reported in several cases also in the case of fusion-evaporation channel for light and medium mass compound nuclei [13]. We report here the results of measurements of the α particle spectra in coincidence with evaporation residues in the decay of the ^{198}Pb nucleus formed at the excitation energies E_x=86 and 103 MeV by using the reaction of ^{28}Si on ^{170}Er at 165 and 185 MeV bombarding energies, respectively. For these reactions a detailed study of the pre-scission channel is available [2]. This gives us, for the first time, the opportunity of comparing directly the α particle spectra in the evaporation and in the fission channel, in order to clarify if there is a clear signature of the different emitter deformation in the two channels.

2 Experimental details

The experiment was performed using the ^{28}Si beams delivered by the XTU Tandem of the Laboratori Nazionali di Legnaro. The target consisted of 100 μg/cm^2 ^{170}Er evaporated onto a 20 μg/cm^2 ^{12}C backing. The ^{170}Er-target isotopic enrichment was 98.9%.

A wide angle electrostatic separator [14] was used to detect the evaporation residues (ER) close to the beam axis, rejecting both the primary beam and the elastic scattered events. The separator, basically a plane capacitor, was 25 cm long and was operated at 10 KV/cm with an entrance collimator that allowed the selection of a slice of the kinematical cone around the beam axis from θ_{lab}=0^o to about θ_{lab}=-10^o. The ER were detected in three 7-strip silicon detectors 300 μm thick (4 ×18 cm^2 total area), placed after the separator at a distance of 117 cm from the target. The identification of the ER was performed by measuring their energy and time-of-flight with the start signal given by prompt γ-rays detected in a BaF_2 cluster.

Charged particles were detected in four large area (25 cm^2) triple telescopes using two silicon detectors (150 and 1000 μm thick) backed by a 3 mm thick CsI(Tl) scintillator with photo-diode read-out. The telescopes were placed at θ_{lab}=40^o, 65^o, 140^o and -65^o in the reaction plane. In the following, only the spectra measured in the telescope at the backward angle θ_{lab}=140^o are presented, in order to minimize possible contributions from incomplete fusion reactions, as discussed in [15].

3 Results and discussion

The center-of-mass energy spectra of the α particles in coincidence with the evaporation residues are reported in Fig. 1. The spectra are compared in the same figure with the maxwellian-like curves which fit the pre-scission component in the analysis of [2]. The error bars of the curves have been computed by using the parametric function and the uncertainties of the parameters both given in [2].

At a first glance, it appears that the spectra are relatively similar in the low energy part, whereas a reduction of the apparent temperature T is evidenced in going from the evaporation to the pre-scission channel.

In order to give a quantitative estimate of the observed difference, we performed a fit of the α spectra to the same

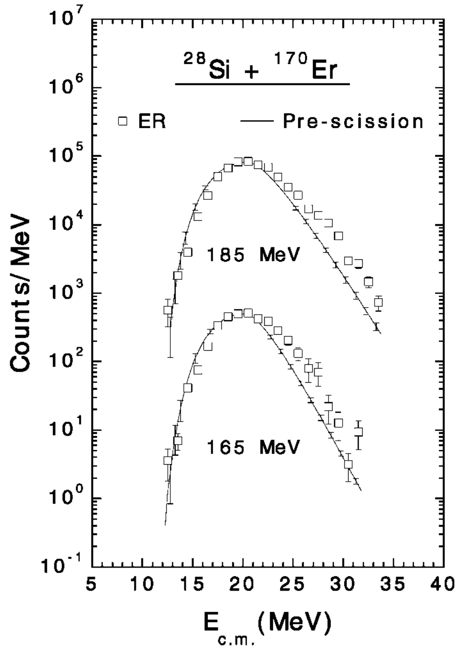

Fig. 1. Center-of-mass α particle spectra measured in coincidence with evaporation residues (*squares*) for the ^{28}Si + ^{170}Er reaction compared to the pre-scission energy spectra from [2] (*lines*)

Maxwellian functional expression used in [2] and reported here for convenience:

$$n(E) = 0 \quad \text{for } E \leq B',$$
$$n(E) = M \times C \times (E - B')^D \times exp(-E/T) \quad \text{for } B' < E < (T + B),$$
$$n(E) = M \times (E - B) \times exp(-E/T) \quad \text{for } E \geq (T + B),$$
where $B' = T + B - T \times D$ and $C = T/(T \times D)^D$.

The parameter T controls the high energy region of the spectrum; B is related to the particle emission barrier and determines the position of the maximum; D controls the slope at low energies and is related to the particle emission barrier diffuseness and penetrability. Finally, M is a normalization parameter and is related to the particle multiplicity.

We developed a program based on *MINUIT* [16] to perform the fit using T, B, D and M as free parameters. The curves that fit the α spectra are shown in Fig. 2 as lines. Table I summarizes the values of the fitted parameters in comparison with the values of the corresponding parameters relative to the pre-scission channel [2].

The interpretation of the gross features of the spectra is rather complex, making impossible a simple explanation of the difference between the two reaction channels. In fact, thermal excitation energy, angular momenta and emitter deformation are not supposed to be the same in the two channels. Furthermore, it is well known that both high energy slope and low energy part of the spectra depend strongly on the length of the decay chain which is

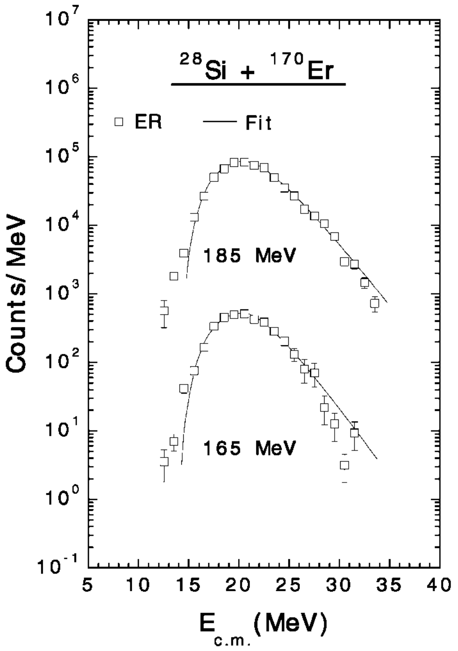

Fig. 2. Fit of maxwellian-like parametric function of [2] (*lines*) to the center-of-mass α particle spectra measured in coincidence with evaporation residues (*squares*) for the ^{28}Si + ^{170}Er reaction

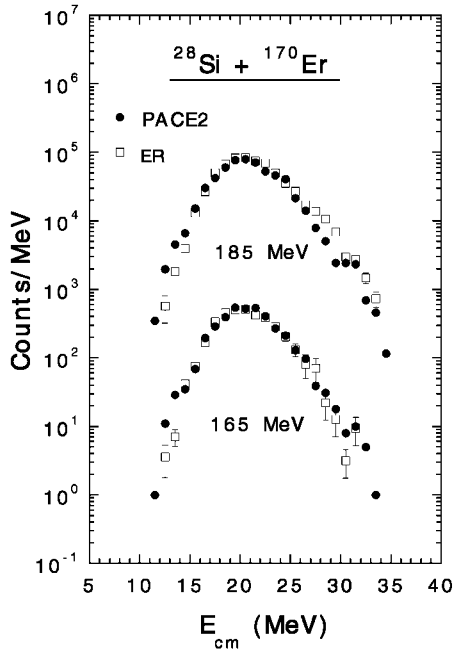

Fig. 3. Center-of-mass α particle spectra in coincidence with evaporation residues (*squares*) for the ^{28}Si + ^{170}Er reaction compared to the PACE2 statistical model predictions (*dots*)

certainly different in the fusion-evaporation and in the pre-scission processes. In particular, the probability for an alpha particle to be emitted after a significant cooling of the initial hot system by neutron evaporation is expected to be negligible in the pre-scission case whether it can not be neglected in the fusion-evaporation one. Because of this effect, the similar shape observed for the low energy part of the spectra do not guarantee comparable deformations of the nucleus in the two cases.

To shed light on the experimental observations, we have performed SM calculations with the PACE2 code [17]. The SM predictions can be used as a tool to disentangle the effects due to the length of the decay chain from those related to the different emitter deformation with the caution that the values of the parameters used in the SM calculations, which are related to physical quantities that change dynamically during the elongation of the fissioning nucleus, should represent only an empirical estimate of the "effective" phase-space available on the average to the charged particle emission during their decay.

Table 1. Parameter values from the fit of the α spectra in the evaporation residues channel (ER) compared to the corresponding ones extracted from [2] for the pre-scission channel (Pre) (see the text for the symbols)

	165 MeV		185 MeV	
	ER	Pre	ER	Pre
T (MeV)	1.90±0.11	1.40±0.03	2.08±0.01	1.67±0.05
B (MeV)	18.57±0.24	18.72±0.28	18.53±0.01	18.72±0.22
D	3.64±0.43	6.44±0.50	3.21±0.01	5.33±0.22

We start our analysis by using standard input parameters without any fission delay. In particular, we have used a level density parameter a=A/9 MeV^{-1} as done in [2] for the analysis of the pre-scission charged particles emission. The latter value was used in both evaporation (a_ν) and fission channels (a_f).

In Fig. 3 the experimental spectra relative to the fusion-evaporation channel are compared with standard SM predictions. It appears that the gross features of the α-particle spectra are well reproduced at both bombarding energies, with an underestimation of the experimental apparent temperature T at the higher bombarding energy. This confirms earlier findings in this mass region [14,15] which indicates the need of using an excitation energy dependent level density parameter to accurately reproduce the charged particles spectra in the fusion-evaporation channel.

We have then considered the case of the pre-scission emission, using for the SM calculations the standard barriers and level density parameter a=A/9 MeV^{-1} that provides a reasonable reproduction of the gross features of the experimental alpha spectra in the fusion-evaporation channel, as discussed above.

As reported in Fig. 4, the comparison between the results from the standard PACE2 and the experimental alpha spectra from [2] shows that the calculation underestimates the production of low energy particles. Moreover, we note that the low energy part of the calculated spectra does not change with the bombarding energy, suggesting that the emission of low energy alpha particles in the

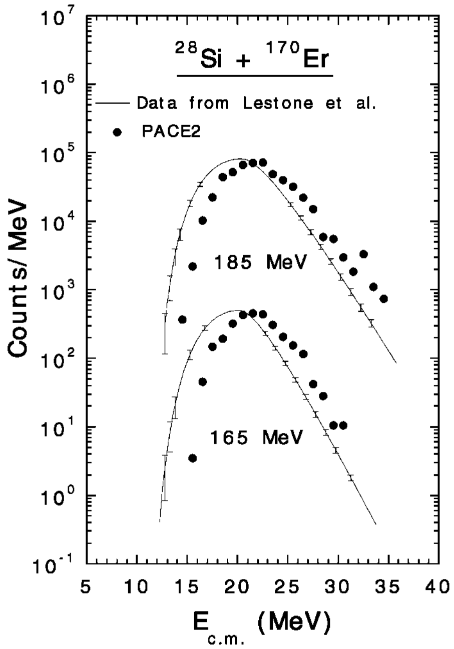

Fig. 4. Comparison between experimental pre-scission α particle spectra (*lines*) for the ^{28}Si + ^{170}Er reaction from [2] and the PACE2 statistical model predictions (*dots*)

pre-scission channel is mainly dominated by the emission barrier effect.

We also note that if the calculated spectra of Fig. 4 are backshifted by ∼2 MeV, the shapes of the experimental spectra are very well reproduced. This supports the fact that the experimental apparent temperatures T are in rather good agreement with the calculated ones.

To complete the investigation, we compare in Fig. 5 the experimental pre-scission proton spectra from [2], for the reaction at 185 MeV, with the results from the PACE2

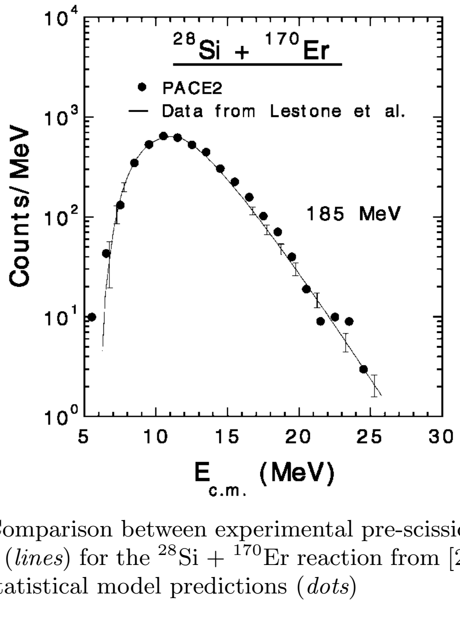

Fig. 5. Comparison between experimental pre-scission proton spectrum (*lines*) for the ^{28}Si + ^{170}Er reaction from [2] and the PACE2 statistical model predictions (*dots*)

code. In this case the experimental distribution is well accounted for by the model calculations indicating that the SM accounts for the gross features of the phase-space open to the proton decay in the pre-scission channel.

We then conclude that the SM with standard input parameters provides a good description of the experimental α-particle spectra in the fusion-evaporation channel and of the pre-scission protons but it fails in reproducing the alpha particle spectrum in the pre-scission channel. This can be taken as direct evidence for the change in deformation (and then of the emission barrier) of the nucleus in route towards fission, with respect to the fusion-evaporation channel. The good reproduction of the proton spectra confirms their already known reduced sensitivity, with respect to the α particles, to the changes in the emission barrier.

Finally, PACE2 calculations were also performed to check the importance of the fission delay on the shape of the predicted particle spectra. For this purpose, a pre-saddle delay of 20×10^{-21} s was introduced in the fission channel, following the prescription of [2]. We found that the shape of the charged particle spectra were scarcely changed by the fission hindrance. The effect of the fission delay is, indeed, to increase the relative weight of the charged particles emitted at higher excitation energies, but this increase does not effectively change the shape of the spectra at the level of accuracy reached in the present Monte Carlo simulations.

In order to estimate the average deformation of the fissioning nucleus from the alpha particle spectra, we have performed further calculations with the evaporative code GANES [18] which simulates the equivalent one step particle emission from a deformed nucleus. The single step approximation can be considered rather good in this case, as the pre-scission emission involves a relatively small number of charged particles. The peculiarity of this code is a consistent treatment of the deformation. In particular, the nuclear shapes are parameterized by Cassini ovals, and the emission barrier is calculated as a function of the birth place of the particle on the nuclear surface, assuming a Coulomb and nuclear potential for a deformed nucleus [19]. The results of these calculations are compared to the pre-fission α spectra from [2] in Fig. 6. A good agreement is obtained assuming an axis ratio b/a=2. The rather low sensitivity of the proton spectra to the deformation induced effects is also confirmed by the GANES calculation which predicts for these particles a shift of only $\simeq$ 600 keV when the emitter is changed from a spherical to a deformed (b/a=2) nucleus.

4 Conclusions

We present in this work the spectra of the α particles emitted in the fusion-evaporation channel in the decay of the ^{198}Pb populated in the reaction of ^{28}Si + ^{170}Er at bombarding energies of 165 MeV and 185 MeV. The present measurement allows for the first time a direct comparison between the shape of the experimental energy spectra of the particles emitted from the ^{198}Pb compound nucleus

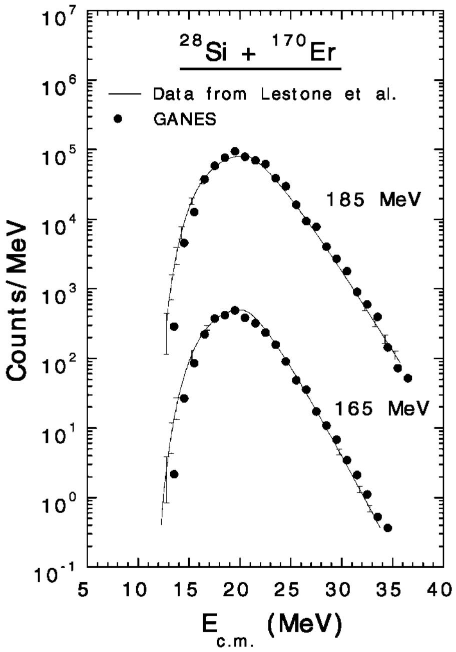

Fig. 6. Comparison between experimental pre-scission α particle spectra (*lines*) for the ^{28}Si + ^{170}Er reaction from [2] and the GANES statistical model predictions for deformed nuclei (*dots*). For details see the text

in the fusion-evaporation and in the pre-scission channels [2].

From an experimental point of view, the spectra in the two channels present the same shape in the low energy region while a difference is observed in the high energy side. In particular the pre-scission spectra feature lower apparent temperatures T.

The α energy spectra in the two channels have been compared with SM predictions using the code PACE2 which accounts for the effects on the spectral shape of the evaporated particles depending on the length of the decay chain, which is different in the pre-scission compared with the fusion-evaporation case. The gross features of the α spectra in the fusion-evaporation channel are reproduced by using standard parameters. With the same set of parameters, the calculated spectra in the pre-scission channel are significantly shifted towards higher energies by $\simeq$2 MeV, with respect to the measured ones. The apparent need of a barrier reduction is interpreted as due to the larger deformation of the fissioning nucleus with respect to the evaporation channel. We note that the same behaviour in the two channels has been observed in the composite system ^{141}Eu at the excitation energy $E_x \simeq 90$ MeV [20]. Furthermore, the need of lowering the emission barrier to account for the average energy of the α particles in the pre-scission channel was already suggested in [1] and [2] by analyzing only the coincidence with fission.

Pre-scission proton spectra from [2] are essentially well reproduced by the standard PACE2 calculations indicating the low sensitivity of these particles to the emitter deformation.

By the calculation performed with the code GANES, the experimental alpha spectra in the pre-scission channel are consistent with an axis ratio of the emitter b/a=2. This axis ratio, typical of superdeformed nuclei in this mass region, has to be taken as an upper limit for the deformation, because of the single step assumption. It is important to note that light lead isotopes $^{196-200}$Pb are predicted to be superdeformed above a spin of about 20$\hbar$ [21]. Giant dipole resonance measurements performed for the ^{200}Pb compound system at excitation energy of about $\sim$70-100 MeV in coincidence with fission fragments seem to demonstrate that nuclei in the pre-scission channel exhibit a deformation parameter $\beta \sim 0.4$ close to the value $\beta = 0.6$ characteristic of the cold superdeformed shape [22]. It is therefore possible to correlate, at least qualitatively, the findings of the present work with the GDR results.

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