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Short note

Possible evidence for the entrance channel effect in reactions leading to ^{170}W*

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Abstract. The decay of ^{170}W* formed in reactions with two different projectile - target combinations was studied. The observed differences in the average number of emitted neutrons suggest an entrance channel effect at the highest excitation energy and angular momentum. It may be explained by different excitation energies of the equilibrated system, resulting from the emission of pre-equilibrium α-particles during a longer fusion time, in the more symmetric reaction.

PACS. 25.70.-z Low and intermediate energy heavy-ion physics – 25.70.Gh Compound nucleus

Entrance channel effects, i.e. differences in various observables measured in the decay of the same compound nucleus (same excitation energy and angular momentum) formed in different reactions, have been investigated [1–5], but with no firm conclusions on their origin or existence. However, recently a quite convincing explanation was suggested by Thoennessen et al. [6]. It was pointed out that the entrance channel effects, observed in some reactions with different projectile-target combinations, may be due to a significant difference in fusion times. In general, longer fusion times are expected for fusion of nearly mass-symmetric heavy-ions, and for heavier systems. This, in turn, may influence the decay of the compound system.

Indeed, calculations with the dissipative fusion model of Feldmeier [7], HICOL, for two reactions, leading to the ^{170}W* compound nucleus at the same excitation energy and maximum angular momentum, show a significant difference between the two reactions (see Fig. 1). The fusion time for the more symmetric (^{60}Ni + ^{110}Pd) reaction is longer, especially at the highest angular momenta, where it reaches a value as high as 10^{-19} s, comparable to the expected particle evaporation time. In addition, for states at high angular momenta the predicted shapes of the compound systems are strongly elongated for a very long time. Large deformation implies lowering of the Coulomb barrier for charged particle emission, which may further enhance pre-equilibrium emission of protons and α-particles.

In order to see if such effects exist and are measurable, we have investigated experimentally the two reactions: ^{60}Ni + ^{110}Pd at bombarding energies of 255 and 260 MeV, and ^{48}Ti + ^{122}Te at 208 and 215 MeV. The bombarding energies and the thin targets ($\approx 450\ \mu$g/cm^2) were chosen carefully to match, in both reactions, the excitation energies of ^{170}W* (E*=56 and 61 MeV) and maximum angular momenta (L_{max}= 59 and 68 $\hbar$, as obtained by the model of Winther [8]). The experiments were performed using the PEX-HECTOR setup assembled at the NBI Tandem Accelerator Laboratory. It consisted of 4 Ge Clusters with BGO Anti-Compton shields (from the EUROBALL collaboration), the HELENA multiplicity filter (38 BaF_2 crystals with a total efficiency of 36%), a Si-Ball (28 Si detectors) and the HECTOR array of 8 large volume BaF_2 detectors for high energy γ-rays.

The difference in the average excitation energies of the fully equilibrated compound system formed in the different reactions, may be studied by observing *the average number of emitted neutrons.* This quantity can be constructed from the measured γ-ray intensities for each evaporation channel σ_{xn} as:

$$<xn>=\frac{2\times\sigma_{2n}+3\times\sigma_{3n}+4\times\sigma_{4n}}{\sigma_{2n}+\sigma_{3n}+\sigma_{4n}}. \qquad (1)$$

An average number of emitted neutrons in the case that one α-particle is also emitted can be defined as:

$$<\alpha,xn>=\frac{1\times\sigma_{\alpha n}+2\times\sigma_{\alpha 2n}+3\times\sigma_{\alpha 3n}}{\sigma_{\alpha n}+\sigma_{\alpha 2n}+\sigma_{\alpha 3n}}. \qquad (2)$$

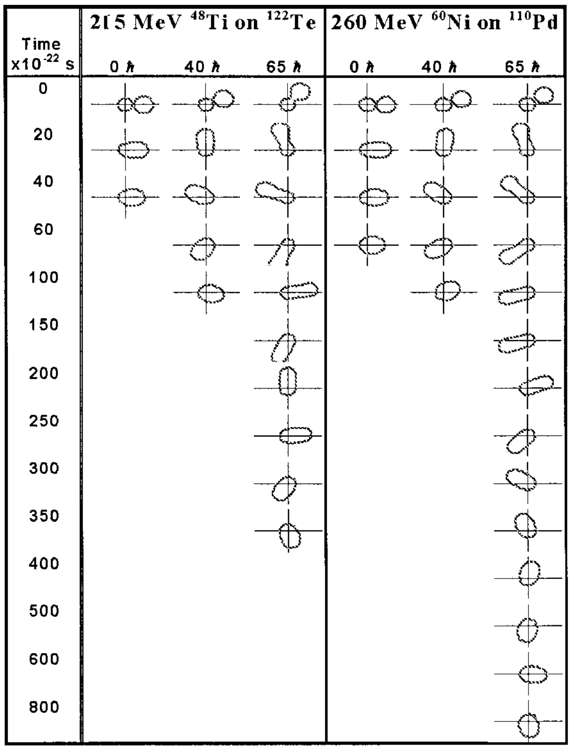

Fig. 1. Shape evolution for the reactions ^{48}Ti + ^{122}Te and ^{60}Ni + ^{110}Pd as calculated by the HICOL code [7]. The calculations stop when equilibrium is reached

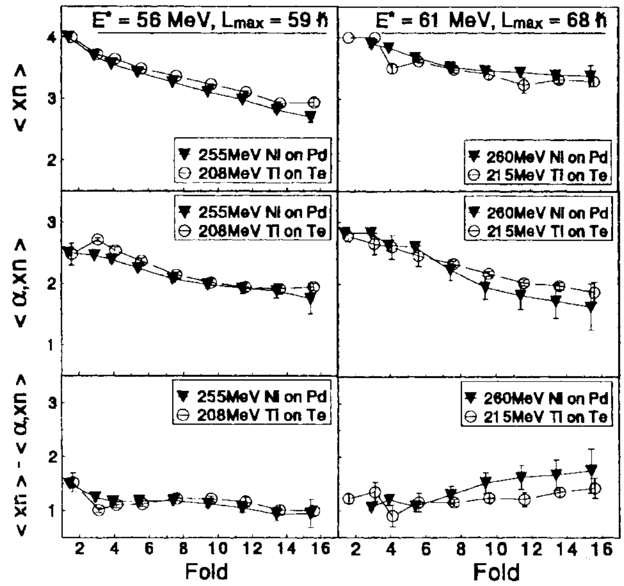

Fig. 2. Average number of emitted neutrons (see text for explanation). The *lines* are to guide the eye

Such quantities are extracted for each pair of reactions, and shown in Fig. 2 as a function of γ-ray fold (which is related to the angular momentum of the residual nucleus) detected in the HELENA multiplicity filter.

The results for E*=56 and 61 MeV are compared in the left and right part of the figure, respectively. The average number of emitted neutrons are compared in the top panels. The magnitude and behaviour are very similar for both energies. A gradual decline with increasing fold is observed, reflecting the rotational energy of the yrast line. It is as expected correspondingly higher for the higher excitation energy. The values of $< \alpha, xn >$ are shown in the middle of the Fig. 2. For E*=56 MeV the values are also almost identical. For E*=61 MeV however, an increasing discrepancy between the two reactions can be observed, for folds higher than 8, e.g. the $< \alpha, xn >$ decreases more steeply for the more symmetric reaction. This can be seen more clearly in the bottom part of Fig. 2, *where the difference* $< xn >$-$< \alpha, xn >$ *is displayed, a quantity which is related to the excitation energy removed by the* α *particle.* It is almost identical and fold-independent for the pair of reactions at E*=56 MeV. Above fold 8 for E*=61 MeV in the more symmetric reaction, the energy removed by an α particle increases strongly with fold, in contrast to the more asymmetric reaction where it is nearly constant. This different behaviour cannot be ascribed to the differences in the angular momentum distributions of the ^{170}W* compound nucleus, because such an effect is not visible in the $< xn >$ values, i.e. when only neutrons are emitted.

This "α-effect" could be explained assuming a higher fraction of α-particles emitted before equilibration in the more symmetric reaction. Since the expected kinetic energy of the particles emitted before the compound system becomes fully thermalized will on the average be larger, such a process will cool down the nucleus before the "normal" statistical decay (after equilibration) begins. Such a cooling process is qualitatively consistent with the scenario expected from the HICOL calculations, and may be responsible for the observed effect. The incomplete fusion process, an another possible explanation, is insignificant, since the angular distributions of alpha particles do not show any forward peaking.

If this effect is authentic, it may be interesting in other contexts as well. The observation of an increased population of superdeformed bands using more symmetric reactions [5] may be explained this way. The longer formation times, leading to pre-equilibrium cooling in more symmetric reactions, may cause the residues to be populated at higher angular momenta, than given by the conventional fission limit. Furthermore, the increased α-cooling effect may enable the observation of hyperdeformed states, which are only expected to become yrast above the fission limit. One could also imagine that it may be important for synthesizing superheavy elements.

Summarizing, the dependence of the decay of ^{170}W*, on the entrance reaction channels ^{48}Ti + ^{122}Te and ^{60}Ni + ^{110}Pd, has been studied. Concerning the neutron evaporation channels the two reactions seem to be identical, but the average number of emitted neutrons as a function of fold for the two reactions is found to be slightly but significantly different for the α-xn channel at the highest bombarding energy. It points to a lower excitation energy of the residual nucleus in the more symmetric reaction at the highest angular momenta. Pre-equilibrium emission of α-

particles is consistent with the long fusion times expected from HICOL calculations.

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