EVAPORATION RESIDUE CROSS SECTIONS AND AVERAGE NEUTRON MULTIPLICITIES IN THE ^{64}Ni + ^{92}Zr AND ^{12}C + ^{144}Sm REACTIONS LEADING TO ^{156}Er

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Evaporation residue cross sections and neutron multiplicity distributions have been measured for the ^{12}C + ^{144}Sm and ^{64}Ni + ^{92}Zr reactions leading to the same compound nucleous ^{156}Er. Statistical model calculations can account for the data in the ^{12}C-induced reaction. In contrast, the inhibition of neutron emission with respect to statistical model predictions seen in ^{64}Ni + ^{92}Zr cannot be explained even with the inclusion of the broad angular momentum distributions required to describe the fusion cross section data.

Significant deviations between experiment and statistical model predictions have been observed for the number of nucleons emitted following certain heavy-ion induced fusion reactions [1–3]. At present, there is no unambiguous explanation for the apparent inhibition of particle emission and more experimental data are needed. In this letter the formation and subsequent decay of the compound nucleous ^{156}Er, where such effects have been observed [1], is studied in the ^{12}C + ^{144}Sm and ^{64}Ni + ^{92}Zr reactions. Fusion cross sections were measured through direct detection of evaporation residues (ER), and multiplicity distributions for neutrons (n) emitted from the compound nucleus were obtained from a separate experiment using gamma-ray techniques.

We find that the inhibition of n-emission reported previously for the 233 MeV ^{64}Ni + ^{92}Zr reaction [1] persists over a wide range of excitation energies. In contrast, good agreement with statistical model calculations is found for the ^{12}C + ^{144}Sm case. It has been suggested [4,5] that the explanation may lie in the presence of high l-tails in the angular momentum distribution for the Ni-induced reaction since the compound nucleus excitation energy above the yrast line would then be reduced, thereby resulting in a lower n-multiplicity. This high l-tail originates from zero-point fluctuations or coupled-channels effects which are thought to be responsible for the observed enhancement of fusion cross sections below the barrier [6].

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The present cross section data extend to energies below the barrier and differences in behavior for the two reactions in the barrier region can be studied. Furthermore, the data can be used in conjunction with data from the Darmstadt–Heidelberg crystal ball [7] where the l-distributions for the two reactions were deduced from the measured γ-ray multiplicity distributions. The two sets of data are complementary and can be used to characterize the l-distributions in greater detail.

Using the method outlined in ref. [8] the fusion cross sections were measured for 200–300 MeV ^{64}Ni and 50–90 MeV ^{12}C beams incident on 180 μg/cm^2 ^{92}Zr and ^{144}Sm targets, respectively. An electrostatic deflector separated the relatively low-energy and highly-charged evaporation residues from the beam. These residues were then identified by their differential energy loss in ΔE–E detector assembly consisting of a common ΔE gas ionization chamber and four silicon detectors covering the angular range from 0° to 4°. For the extremely low-velocity evaporation residues from the ^{12}C + ^{144}Sm reaction (E_{recoil} < 6 MeV) unambiguous identification through time-of-flight was achieved with a slow beam-sweeper (410 ns on/2.5 μs off). The data presented below were corrected for the efficiency of the deflector and the detector geometry following Monte Carlo ray-tracing calculations (see ref. [8] for details). The uncertainties associated with this procedure are included in the 15% systematic error of the cross sections.

Neutron-multiplicities were deduced from yields of individual xn-channels, obtained from separate γ-ray measurements in which 55–75 MeV ^{12}C and 225–295 MeV ^{64}Ni beams bombarded 1 mg/cm^2 targets. Effective beam energies were obtained following the procedure described in ref. [1]. The relevant spectra were measured with a Ge detector positioned at 0° with respect to the beam direction. Singles spectras as well as spectra in coincidence with one or more elements of an array of eight NaI detectors surrounding the target were used to identify the different xn-evaporation channels. The relevant level schemes, γ-ray anisotropies and detector efficiencies were taken into account, and the associated uncertainties were included in the systematic error. Minor corrections for the isotopic composition of the targets (isotopic enrichment $\gtrsim$97% in all cases) were also applied.

Fig. 1a presents the measured ER cross sections

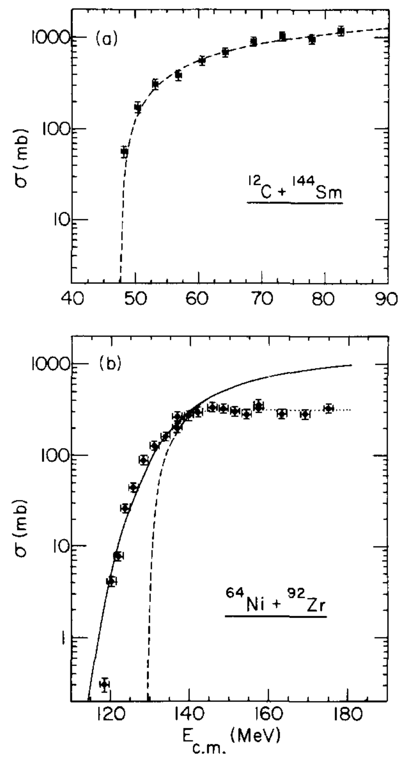

Fig. 1. Evaporation residue cross sections for the ^{12}C + ^{144}Sm (a) and the ^{64}Ni + ^{92}Zr (b) reactions as a function of the beam energy. An overall 15% systematic uncertainty in the cross section is not included in the figure. The curves refer to calculations discussed in the text; i.e. the dashed curve is a calculation with the model by Swiatecki [9], the solid line includes the effect of barrier fluctuations [10] and the dotted line represents σ(ER) calculated from the fusion cross sections (solid line). The energies given in the figure have been corrected for target thickness. The data in (a) have been obtained by scaling the highest-energy data points to the calculation (see text). This procedure does not apply to (b) where absolute cross sections are presented.

for the ^{12}C + ^{144}Sm reaction. Statistical model calculations discussed below indicate that the fission probability is essentially zero at the beam energies discussed here and, hence, the measurements represent the total fusion yield. In this case the residues are characterized by small recoil velocities and by a rather broad angular distribution. Both characteristics severely affect the calculation of the absolute transmission of the deflector system. While this does not affect the relative values of the cross sections, precise absolute values are difficult to deduce. For this reason, the data presented in fig. 1a have been obtained by scaling the highest-energy data points to a curve obtained from a calculation based on the dynamical fusion model by Swiatecki et al. [9]. Calculations performed with other models such as those proposed by Bass [11] or Kailas and Gupta [12] yield equivalent results. As can be seen from fig. 1a the trend of the data is very well reproduced over the entire energy range under study.

Fig. 1b presents ER cross sections for the ^{64}Ni + ^{92}Zr reaction. Here the velocities of the recoiling ER are large and absolute cross sections are derived from the measurements directly. The dashed line represents a calculation similar to the one given in fig. 1a. Clearly, this calculation does not agree with the data: at energies below the barrier (E_{cm} = 132.7 MeV) the cross section is much larger than predicted, and above the barrier the measurements fall below the computed values. Thus subbarrier enhancement of the fusion cross section is observed for this reaction, a phenomenon found in many reactions with heavy ions [‡1]. The deviations at higher energies can be attributed to the onset of fission, a process which escapes detection in the present measurement.

The solid line in fig. 1b represents a fusion cross section calculation based on the dynamical fusion model by Swiatecki et al. [9] but modified to include the fluctuations in barrier height based on the model of Esbensen [10]. Within this model the parameter σ_λ = 0.61 fm needed to fit the data was larger than expected from the known B(E3) and B(E2) values of the lowest strongly excited inelastic states (σ_λ = 0.42 fm) but probably not unreasonable if one accounts for the fact that other inelastic (and transfer) channels should be included. The parameters within the dynamical fusion model (extrapush) were chosen from the recent systematic study of fusion and fusion–fission in the ^{58,64}Ni + ^{A}Sn systems [14].

In order to obtain the ER and fission cross sections, the calculated fusion cross sections (solid line fig. 1b) have been introduced into statistical calculations with the code CASCADE [15]. This approach is similar to the one presented by Lesko et al. [14]. As in ref. [14], use was made of the Sierk fission barriers [16], where the surface of the rotating liquid drop model is smeared out by an exponential folded into a Yukawa shape.

‡1 For a recent revew see for example ref. [13].

The partial wave distribution of the compound nucleus reflected the coupling of the quasi-elastic channels discussed above through the value used for the diffuseness parameter d of the entrance channel transmission coefficients of CASCADE ($T_l = 1/\{1 + \exp[(l - l_0)/d]\}$, $\sigma_l = \pi\chi^2(2l + 1)\,T_l$). This code was also modified to include enhancement of collective E2 transitions parallel to the yrast line and E1 deexcitation through the giant dipole resonance [1]. The experimentally established yrast lines are used as well. The level density parameter used was $a = A/12$, which gives agreement with the neutron spectra measured for the decay of this particular compound nucleus [1]. The sensitivity of the cross section calculations to the value of this parameter was found to be small (calculations with the more commonly used $a = A/8$ value for example render essentially the same result). The dotted line of fig. 1b illustrates the agreement between the measured and calculated ER cross sections. The calculations were performed with $d = 4\hbar$, a value derived from the measured angular momentum distribution [7] for this reaction at E_{cm} = 139 MeV. Calculations with $d = 7.5\hbar$, the value deduced in ref. [14] for ^{58,64}Ni + ^{A}Sn reactions yields similar results.

The same statistical model calculations discussed above were used to obtain the average n-multiplicities at different beam energies and the excitation functions for the various xn channels. Fig. 2 presents a comparison between measured and calculated n-multiplicities as a function of the compound nucleus excitation energy for the two reactions under discussion. For the ^{12}C + ^{144}Sm reaction the fusion cross sections were used as input; i.e. the l-distribution of the form given above was used with $d = 2\hbar$ and l_0 was adjusted within CASCADE to reproduce the fusion cross sections (solid line in fig. 1a). Typical values of l_0 are given in table 1. The agreement between theory and experiment of the n-multiplicities is very good (fig. 2a). Furthermore, the excitation functions for the different xn-channels (not shown) are also well reproduced. Predictions for reaction channels involving the emission of charged particles could not be tested in detail since the required spectroscopic information on the final nuclei is in many cases unavailable. In those few cases where it is possible good agreement was found. Thus, it is concluded that statistical model calculations are able to describe the decay of the ^{156}Er nucleus formed in the ^{12}C-induced reaction.

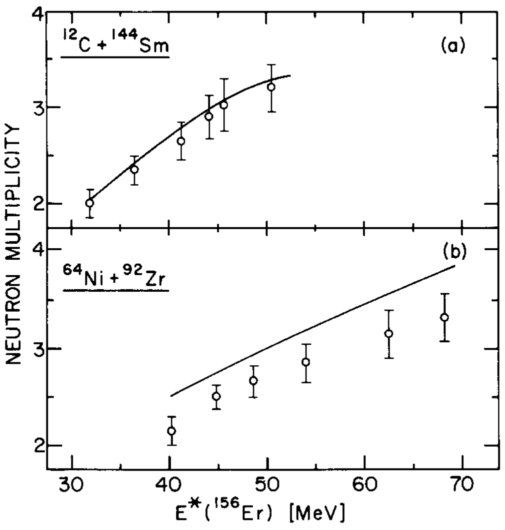

Fig. 2. Average neutron multiplicities for the $^{12}C + ^{144}Sm$ and $^{64}Ni + ^{92}Zr$ reactions as a function of compound nucleus excitation energy. Only the 1–4 n-channel yields were used to compute the theoretical and experimental n-multiplicities since the level schemes for channels corresponding to higher n-evaporation are not known. The solid lines represent the results of statistical model calculations.

In contrast to the agreement noted for $^{12}C + ^{144}Sm$, a strong discrepancy is seen for the ^{64}Ni-induced reaction (fig. 2). The calculations were performed with $d = 4\hbar$ and with the fitted fusion cross sections (solid line in fig. 1b). The measured n-multiplicities are lower than the predicted values by 0.35 neutrons on the average. Furthermore, the general shape of the measured excitation functions for the xn-channels (not shown) are not well reproduced. Thus, the inhibition of neutron emission presented in ref. [1] for a single beam energy is shown to persist over a wide range of excitation energies and angular momenta. This discrepancy is of the same order as the one reported in refs. [2,3] and the effect is seen here for a compound nucleus with neutron number in excess of 82, in line with the dependence suggested by Stwertka et al. [2].

It should be emphasized that the calculations presented in fig. 2b for the $^{64}Ni + ^{92}Zr$ reaction incorporate the broad angular momentum distributions ($d = 4\hbar$) discussed above. As a result the discrepancies between the measurements and the calculations at the lower excitation energies are somewhat reduced with respect to the results of ref. [1]. As in refs. [1,2] variations within acceptable limits of other parameters in the statistical calculations, such as the E1 and E2 strength or the level density parameter, do not yield satisfactory agreement with the data. For example, variations of the level density parameter from $A/8$ to $A/14$ or changes in the diffuseness d from $4\hbar$ to $7.5\hbar$ in CASCADE calculations (corresponding to an excitation energy of 49 MeV) would change the n-multiplicity by less than 5%. Moreover, the E1, E2 strengths are constrained by the giant dipole resonance energy-weighted sum rule and by experimentally measured γ-ray yields. These findings rule out the suggestion [4,5] that the inhibition of n-emission is due to large distortions of the angular momentum distribution. It should be noted that the presence of very high partial waves in the fusion cross section would not automatically imply reduced n-multiplicities since CASCADE calculations indicate that they contribute mainly to fission and not to the ER's (the fission cross section increases rapidly over the ER cross section for $l > 50\hbar$).

Finally, the ER cross sections [σ(ER)] reported here and the spin distributions derived from γ-multiplicity measurements [7] provide two data sets which are not only complementary but also allow a cross-check between the sets. The data can be combined to give the absolute ER cross section for each partial wave (σ_l) through the constraint: sum$(\sigma_l) = \sigma$(ER). Thus σ_l can be immediately obtained from the spin distribution results (ref. [7]). In principle, a measurement of σ(ER) by itself does not yield σ_l. However, by adopting the form given above for T_l with the diffuseness given by the spin distribution measurement, σ_l can be computed. For a compound nucleus excitation energy of 47 MeV data are available to compare

Table 1
Typical l_0 values derived from the calculated fusion cross sections with the expressions given in the text.

E^* (MeV)	$^{64}Ni + ^{92}Zr$		$^{12}C + ^{144}Sm$	
	E_{cm} (MeV)	l_0 ($\hbar$)	E_{cm} (MeV)	l_0 ($\hbar$)
50	141.8	51.5	68.1	29.5
47	138.8	46.0	65.2	27.0
45	136.8	41.0	63.1	25.5
40	132.1	29.0	58.2	21.0

σ_l derived by the two methods for the two reactions under discussion. For the ^{12}C case the agreement is excellent [17], with $l_0 = 27 \pm 3\hbar$ obtained with both methods. For the ^{64}Ni case there is agreement within the errors: l_0 values of 38 ± 4 and $46 \pm 4\hbar$ are derived from the spin distribution and $\sigma(ER)$ measurements, respectively [17].

In summary, we have observed that inhibition of neutron emission persists over a wide range of excitation energies and angular momenta for the rather mass symmetric $^{64}Ni + ^{92}Zr$ fusion reaction, while it is absent in the more asymmetric $^{12}C + ^{144}Sm$ reaction. For the latter reaction a consistent picture of fusion with subsequent statistical decay of the compound nucleus accounts for the measured data (cross sections and n-multiplicities). For the former reaction, the presence of coupled-channel effects and/or zero-point fluctuations manifests itself through the enhancement of the fusion cross section below the barrier and the presence of large fission cross sections at higher energies. Both features can be accounted for in model calculations which include tails towards high values in the angular momentum distribution. However, the inclusion of these high l-tails is unable to account for the suppression of neutron emission. All the data now available on the decay of ^{156}Er rule out all the obvious explanations for this suppression, i.e. high l-tails, anomalously large neutron energies, very large gamma decay widths and uncertainties in the location of the yrast line. It is concluded that the original suggestion of trapping in a superdeformed minimum made in ref. [1] should be pursued further. Experiments along these lines are in progress.

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