1-1-2011

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EPJ Web of Conferences **17**, 05002 (2011)
DOI: 10.1051/epjconf/20111705002


# Fusion of $^{60}$Ni + $^{100}$Mo below barrier.

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**Abstract.** The fusion cross section of $^{60}$Ni + $^{100}$Mo has been measured down to microbarn level, looking for hindrance at low energy, in a system with positive Q-values for neutron transfer. The measured cross sections look similar to those of the nearby $^{64}$Ni + $^{100}$Mo, but no conclusive statement can be made at this stage, as to the onset of hindrance in this system.

## 1 Introduction

Deep sub-barrier fusion has been the source of a improved understanding of the nuclear fusion process in recent years [1-5]. Fusion hindrance at low energy, in particular, i.e. the drop in fusion cross section below calculations that reproduce higher energy data, appears to be a general phenomenon, on which theory is finally shedding some light. However, it remains a little explored field with many unanswered questions.

The initial motivation for the present experimental study was to investigate the effect of neutron transfer on the fusion hindrance. Theoretically, the effects of neutron transfer on fusion enhancement have been debated since the '80s, but no general consensus has emerged because of the complexity of the problem which forces the use of different simplifications for computational purpose. However, the correlation between the availability of positive Q-values for neutron transfer and fusion-enhancement below barrier, at the empirical level, is impressive. One of the best cases is probably the set of precisely measured fusion excitation functions for $^{40,48}$Ca + $^{90,94,96}$Zr [6]: the huge sub-barrier enhancement of $^{48}$Ca + $^{94,96}$Zr compared to other systems correlates nicely with neutron-transfer Q-values, but not so much with the structure properties of the participating nuclei. Unlike inelastic excitations, that determine the structure of the fusion excitation function around the barrier (the "barrier distribution") the effect of neutron transfer may show up at lower energies, possibly in the same energy range where fusion hindrance is expected..

Another qualitative reason to expect some effect is that neutron transfer is often viewed as a precursor of the "neck formation", i.e. a different (adiabatic) pathway to compound nucleus formation [5, 7] in alternative to the "sudden approximation" which has been so successful with light to medium-heavy ions, at least for energies around the Coulomb barrier.

## 2 The experiment

The particular system was chosen because fusion hindrance has already been observed in the nearby $^{64}$Ni + $^{100}$Mo [8] a system with similar low-lying quadrupole and octupole vibrational properties (Table 1) but large, positive Q-values for neutron transfer unlike with $^{64}$Ni (see Table 2).

The measurement was performed with the Fragment Mass Analyzer (FMA) of the Argonne National Laboratory, equipped with a multiparametric focal plane detector described in [9]. This detector consists of three parallel grid avalanche counters (pgac), each one yielding X and Y position and timing; two transmission ionization chambers (tic) are sandwiched between the pgac's, and the ions are finally stopped in a Bragg chamber. Overall, there were seven energy-loss signals besides two time-of-flight, positions etc. Such redundancy is crucial to select evaporation residues (ER) against a much larger background of scattered beam particles and target recoils.

**Table 1.** Collective vibrational levels of the nuclei considered..

| Nucleus | $\lambda^+$ | E (MeV) | $\beta_\lambda$ |
|---|---|---|---|
| $^{100}$Mo | 2+ | 0,54 | 0,231 |
| | 3- | 1,91 | 0,21 |
| $^{64}$Ni | 2+ | 1,35 | 0,165 |
| | 3- | 3,56 | 0,193 |
| **$^{60}$Ni** | 2+ | 1,33 | 0,20 |
| | 3- | 4,04 | 0,16 |

**Table 2.** Q-values for neutron pickup.

| System | +1n | +2n | +3n | +4n |
|---|---|---|---|---|
| $^{64}$Ni+$^{100}$Mo | -2,19 | 0,86 | -2,00 | -1,01 |
| $^{60}$Ni+$^{100}$Mo | -0,47 | 4,20 | 2,40 | 5,23 |

Even so, an unexpectedly large background, that could not be completely rejected, prevented us from reaching below the microbarn level.

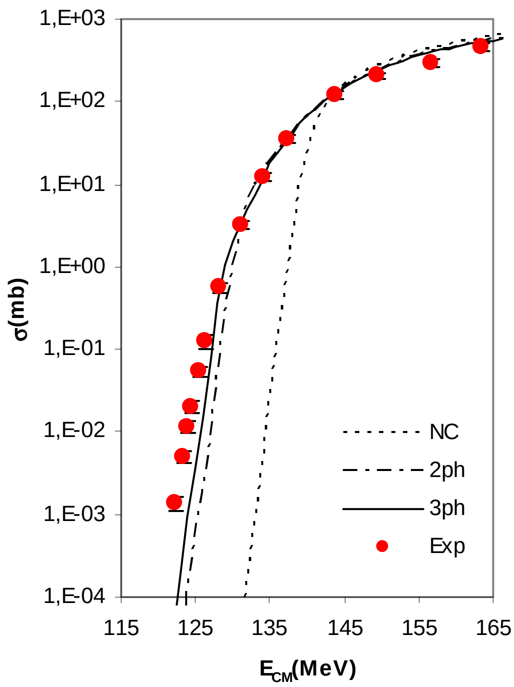


**Fig. 1.** Experimental and calculated fusion excitation functions for the $^{60}$Ni + $^{100}$Mo reaction. *NC* means "no coupling", *2ph* and *3ph* stand for 2- and 3-phonon channels (see text for details).

The $^{60}$Ni beam was delivered by the ATLAS accelerator, at 16 energies ranging from 194 to 262 MeV, and beam intensities typically 100-200 pnA and up to 400 pnA. The $^{100}$Mo targets were isotopically enriched to 97.4% and 34 and 39 μg/cm$^2$ thick, on 40 μg/cm$^2$ thick carbon backings. A carbon reset foil, 20μg/cm$^2$ thick, was placed downstream of the target and helped bring the charge state distribution to a narrower and more regular equilibrium shape. Charge state distributions were scanned carefully at a few energies; and turn out to be well reproduced by the Sayer formula [10] shifted up one unit. In most cases four charge states were measured, sometimes two and only at a few low energies a single state was measured.

## 3 Results and discussion

Cross sections are obtained from the mass and charge-state integrated evaporation residues (ER), after correcting for detector efficiency and beam transmission through the FMA. Absolute normalization is obtained by normalizing to elastically scattered beam particles in a monitor detector at 45° to the beam direction. Only at the largest energy some deviation from pure Rutherford scattering can be expected, however it should be small compared to other sources of error and no correction was applied here.

The transmission was calculated with a modified version of GIOS, using as input the distributions obtained from PACE2 evaporative calculations. In these preliminary results, a 20% error is attributed to transmission values, added in quadrature to the statistical errors. At the three higher energies the ER cross section has been corrected for fission, as calculated with PACE2.

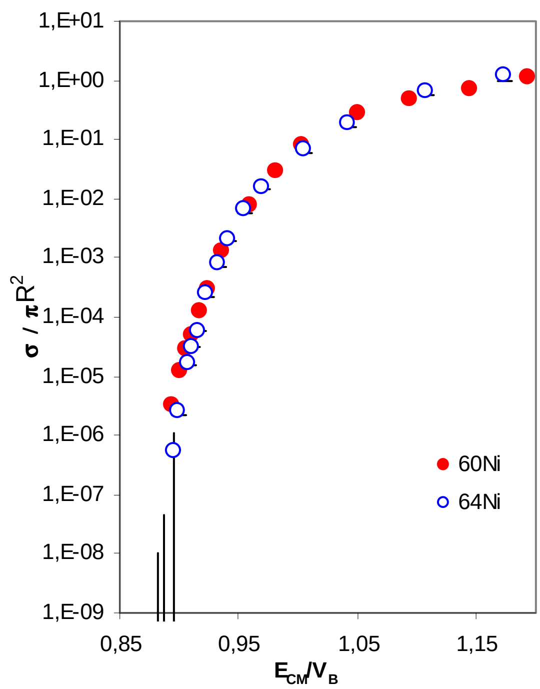


**Fig. 2.** Comparison of the fusion excitation functions of $^{60}$Ni + $^{100}$Mo (full circles) and $^{64}$Ni + $^{100}$Mo (open circles). For $^{64}$Ni + $^{100}$Mo only upper limits were obtained at the two lower energies

The resulting cross section is plotted in figure 1 together with coupled channels (CC) calculations with the code CCFULL [11]. The Woods-Saxon potential was chosen to reproduce the higher energy points of $^{64}$Ni + $^{100}$Mo [8] and "scaled" to this system by keeping the same parameters $V_0$, $r_0$, $a$. In the spirit of the code, the input parameters are the "deformation lengths" $\beta_2$, $\beta_3$ (from the experimental transition probabilities) of the low lying $2^+$ and $3^-$ collective vibrational states. Up to two-phonon states were included in the calculation for the quadrupole excitations, while for $^{100}$Mo also the three-phonon state was allowed (as in [8]); for the high-lying octupole vibration of $^{60}$Ni only one phonon was allowed. The labels "2-ph" and "3-ph" in figure 1 refer to the reaction channels: it is the maximum number of phonons included in the calculation, being the sum of target plus projectile.

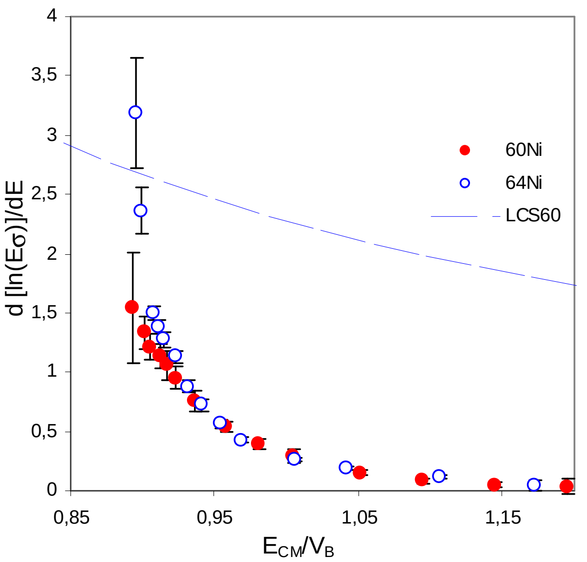


**Fig. 3.** Logarithmic derivatives of the $^{60,64}$Ni + $^{100}$Mo systems under discussion. The LCS line (constant astrohpysical S-factor [12]) refers to the $^{60}$Ni case, but the other one is very close.

Aside for the large enhancement with respect to the no-coupling limit, one notices a residual excess cross section at low energy, but the slope does not seem significantly different from the CC calculations. The impossibility to measure a few more points at lower energy, as explained, does not allow do draw conclusions on this point.

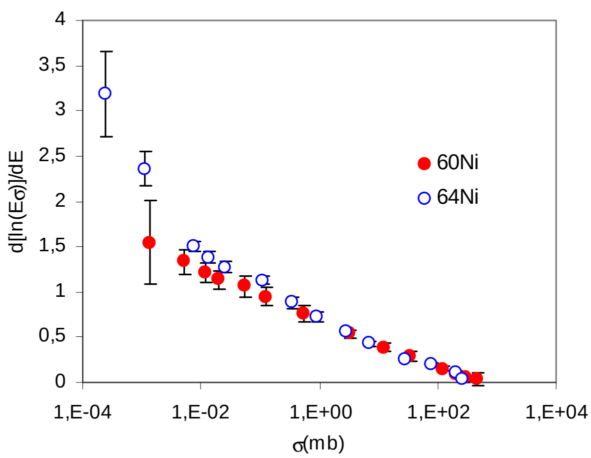


**Fig. 4.** As figure 3, now as a function of cross section.

In figure 2, the excitation function is compared with $^{64}$Ni + $^{100}$Mo in the "reduced scale" representation which removes trivial geometrical effects.

The slope at low energy is slightly smaller in the present system, but the best way to compare the low energy slope is by means of the logarithmic derivative [12], as seen in figure 3. Notice the use of a reduced energy scale in the horizontal axis. In this plot, the logarithmic derivative of $^{64}$Ni + $^{100}$Mo has been recalculated with a "Gaussian smoothing" (2 MeV fwhm) of the excitation function. The same procedure was applied to the present data. A difference in slope is more apparent but, because of the large error bars and taking into account that our data are still somewhat preliminary, a conclusion is premature.

In two recent papers [13, 14] the logarithmic derivative has been plotted versus fusion cross section, rather than energy. This is shown in figure 4 for $^{60,64}$Ni + $^{100}$Mo.

Just like the popular reduced-scale representation, the rationale behind that is to be found in the limit of the Wong function: it turns out that in this representation all systems practically coalesce at high energy, therefore this one seems to be a convenient representation, that does not require normalization.

While the recent research in deep sub-barrier fusion has concentrated on the riddle of systems with positive fusion Q-values, medium heavy systems, like the one discussed here, could be a first step towards spanning the gap between systems which are successfully described in the sudden approximation, and the heavier ones that can only be understood in the adiabatic limit.

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