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The influence of the 2-neutron elastic transfer on the fusion of ^{42}Ca + ^{40}Ca

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Abstract

Strong coupling to a single channel with zero Q-value is predicted to produce a characteristic fusion barrier distribution with two peaks, one on each side of the original uncoupled Coulomb barrier. In practical cases, only coupling to an elastic transfer channel may produce such a distribution which, however, has never been observed sofar, probably because low-lying surface vibrations usually have a dominant role, and this may obscure the two-peak structure. The case of the two-neutron (2n) elastic transfer in ^{42}Ca + ^{40}Ca is particularly attractive, because of the relatively rigid nature of the two nuclei.

We have measured the fusion excitation function of this system using the ^{42}Ca beam of the XTU Tandem of LNL on a thin ^{40}Ca target enriched to 99.96% in mass 40. Cross sections have been measured down to $\leq$1 mb. The extracted barrier distribution shows clearly two main peaks. We have performed preliminary CC calculations where the 2^+ coupling strengths have been taken from the literature and the schematic 2n pair transfer form factor has been used, with a deformation length σ_t= 0.39 fm. The excitation function is well reproduced by

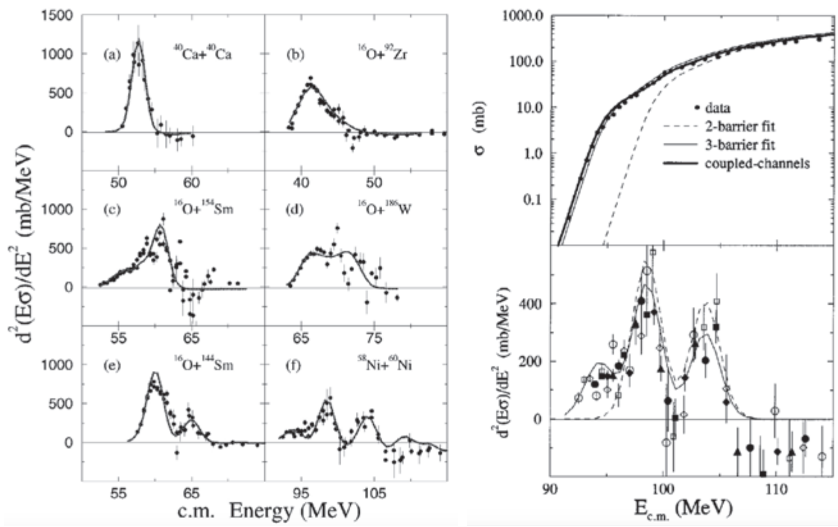


Figure 1: Left: Experimental fusion barrier distributions for six different systems, showing the sensitivity to the structure of the colliding nuclei, and to the nature of couplings involved. Right: Top panel: The measured fusion excitation function for ^{58}Ni + ^{60}Ni is compared with phenomenological fits and with CC calculations. Bottom panel: The barrier distribution is compared with the phenomenological fits.

the calculation including the 2n transfer channel. However, including the octupole excitations destroys the agreement.

1 The fusion barrier distributions

In the near- and sub-barrier fusion of heavy ions, several measurements exploited the concept of a fusion barrier distribution (BD) to identify the nature of couplings responsible for cross section enhancements. Different shapes of barrier distribution are predicted for the coupling to low-energy surface vibrations and for the transfer of one or more nucleons (see Fig. 1, left panel for some well-known examples [1]). Multi-phonon excitations have been shown [2] to become dominant for medium-heavy nuclei and produce complex fusion barrier distributions, in some cases with discrete structures [3, 4]. Moreover, below the lower energy limit of such distributions, it has been discovered in recent years [5] that fusion excitation functions show a sharp decrease (named “hindrance”) with decreasing energy, well below the expectations based on standard coupled-channels (CC) calculations.

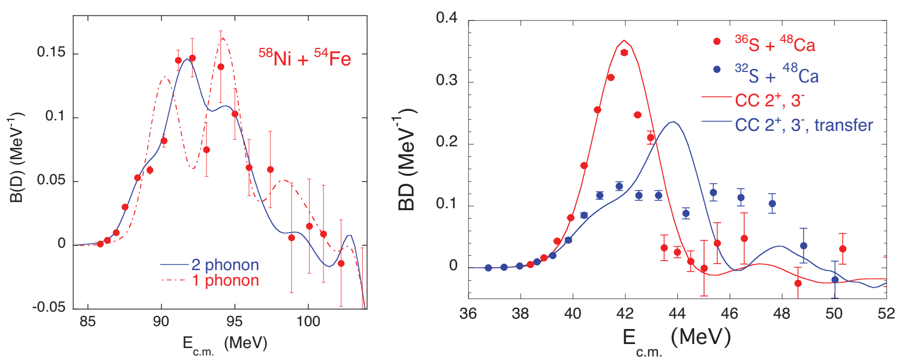


Figure 2: Left: The barrier distribution of ^{58}Ni + ^{54}Fe. Right: Fusion barrier distributions of the two systems ^{36,32}S + ^{48}Ca as derived from the experimental data and calculated within the CC model (see text for comments).

However, identifying the effect of coupling to transfer channels has often been elusive, when deduced from comparing with calculations. One might say that transfer couplings are clear only in the cases where the experimental evidence is conclusive in itself.

2 Coupling to Q=0 channels

A striking fusion barrier distribution is predicted for strong coupling to a single channel with zero Q-value. Irrespective of the type of coupling (phonon or transfer channel) one should obtain in this case a roughly symmetric distribution possessing two peaks, one on each side of the original uncoupled Coulomb barrier.

In practical cases, only coupling to an elastic transfer channel (of one or two nucleons) may produce such a distribution which, however, has never been observed sofar, because low-lying surface vibrations usually have a dominant role. This complicates and may totally obscure the two-peak structure. One should also keep in mind the model calculations of Ref. [6], where it was shown that one obtains a two-peak BD for Q=0 only in the case of *simultaneous* transfer of any number of nucleons, while the number of peaks equals the number of channels when the transfer is sequential.

For the fusion of combinations of Ni isotopes both phonon and transfer channels may play an important role. Several years ago, we decided, therefore, to perform a precision experiment on the system ^{58}Ni + ^{60}Ni [4], so to investigate the possible role of the 2-neutron elastic transfer channel.

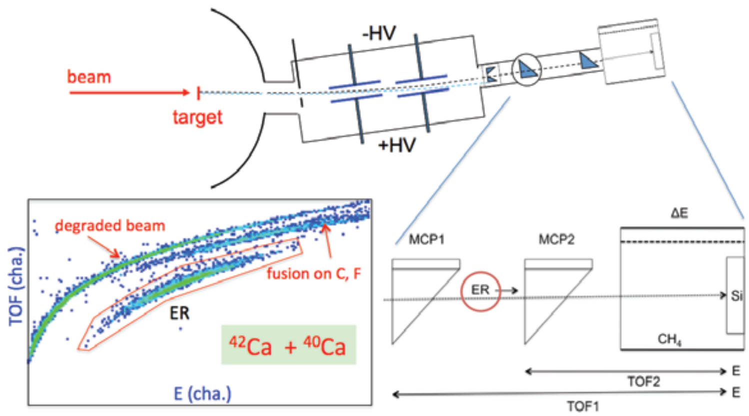


Figure 3: Scheme of the set-up used for the detection of fusion-evaporation residues in the experiment on ^{42}Ca + ^{40}Ca.

The phonon excitation energies and vibrational deformation parameters are very similar for those two nuclei, and the result of the experiment was that multi-phonon surface vibrations determine the shape of the barrier distribution to a large extent, thus preventing to observe the possibly underlying symmetric distribution expected for the 2n elastic transfer. The right panel of Fig. 1 is taken from the original paper on ^{58}Ni + ^{60}Ni [4] and illustrates this situation.

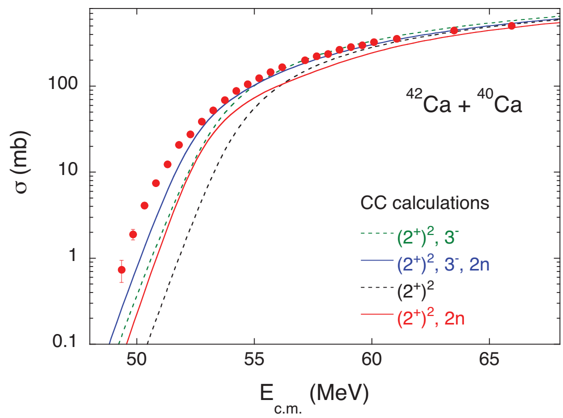
A similar situation was found for ^{58}Ni + ^{54}Fe a few years later [7], where the complex structure of the barrier distribution closely resembles the BD of ^{58}Ni + ^{60}Ni, and it is nicely reproduced by CC calculations, see Fig. 2 (left). The fusion dynamics is dominated by low-energy surface modes in this case too, and little space is left for the possible influence of the α-elastic transfer.

By the way, strong transfer couplings tend to produce wide and flat barrier distributions, even if Q is not zero. A recent example is given by the measurement on ^{32}S + ^{48}Ca [8], whose BD is reported in Fig. 2 (right) in comparison with the case of ^{36}S + ^{48}Ca where transfer does not play any role.

3 This experiment

The case of ^{42}Ca + ^{40}Ca seemed to us particularly attractive, because:

- ^{40}Ca is a magic nucleus with double shell closure, having a strong



	I^π	E_x(MeV)	β_C	β_N
^{40}Ca	2+	3.905	0.12	0.11
	3-	3.747	0.41	0.28
^{42}Ca	2+	1.525	0.25	0.19
	3-	3.447	0.30	0.16

Figure 4: Measured fusion excitation function of ^{42}Ca + ^{40}Ca compared to CC calculations. The structure information on the two nuclei used in the calculations is shown in the Table on the right (see text).

octupole vibration at high energy (3.737 MeV). Its effect on sub-barrier fusion is expected to be mainly a potential renormalization "rigidly" shifting the barrier distribution to lower energies;

- ^{42}Ca, with two neutrons in the $1f_{7/2}$ shell, is rather rigid with a weak 2^+ quadrupole excitation at 1.524 MeV. This makes it plausible that the effect of elastic 2-neutron pair transfer can be recognized in the barrier distribution of this system.

We report here on the measurement of the near- and sub-barrier excitation function of ^{42}Ca + ^{40}Ca, where no data have been obtained sofar. In recent years we have investigated the fusion of various Ca+Ca systems down to very low cross sections [9–11], and the 2-neutron pick-up channel has been found to play an important role in the fusion of the asymmetric system ^{40}Ca + ^{48}Ca. The CC analysis of those data gives us an idea of the coupling strength to be associated to the 2n transfer channel.

The ^{42}Ca beam from the XTU Tandem accelerator of LNL has been used, on thin ^{40}CaF$_2$ targets $\sim 50\mu$g/cm^2, so to minimize beam energy corrections and straggling effects. The ^{40}Ca target isotopic enrichment was very high (99.96%). The evaporation residues (ER) have been detected by the electrostatic separator set-up (Fig. 3), already used for several sub-barrier fusion measurements at LNL.

The fusion excitation function has been measured in a wide energy range around the Coulomb barrier. It is shown in Fig. 4, together with the results

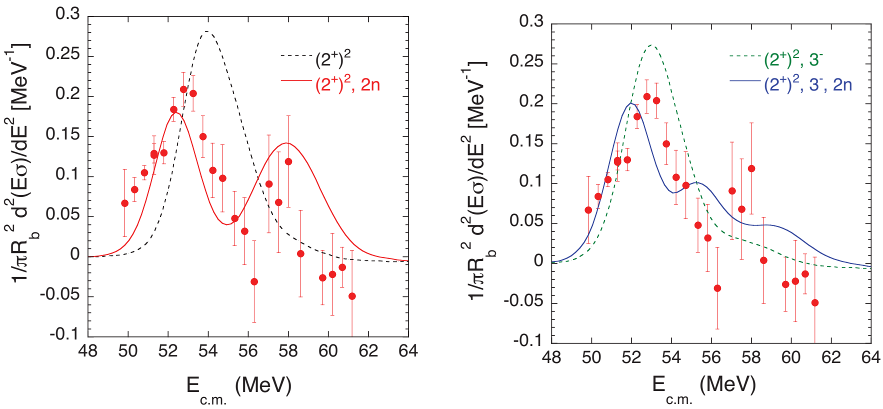


Figure 5: Extracted barrier distributions and CC calculations.

of CC calculations described in the next Section. The energy step and the statistical errors in the measured points were small enough, and this has allowed us to extract the barrier distribution with good accuracy. The BD is shown in Fig. 5, and two nice peaks can be clearly seen.

4 Results and CC calculations

We have performed CC calculations, using the code CCFULL [12], whose results are shown in Fig. 4. The 2^+ and 3^- coupling strengths have been taken from the literature. Two quadrupole phonons have been included and the Akyüz-Winther potential [13] $U(r)$ has been slightly modified to better fit the cross sections in the barrier region. The 2n pair transfer is schematically described (simulated) by the form factor [14]

$$V_t = -\sigma_t dU(r)/dr$$

In the present calculations σ_t has been given the value 0.39 fm best fitting the data on ^{40}Ca + ^{48}Ca [9].

One sees that adding both the octupole modes and the 2n transfer to the quadrupole excitations, produces a large effect on the cross sections. The full calculation still underestimates the sub-barrier excitation function. But let us see what happens when the barrier distribution is considered.

When only quadrupole excitations are included (left panel), the additional transfer mode produces a nice two-peak structure closely resembling

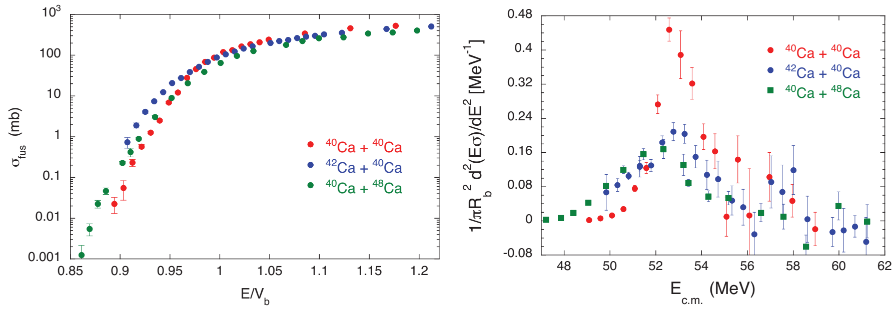


Figure 6: Left: The three excitation functions of the systems ^{42}Ca + ^{40}Ca, ^{40}Ca + ^{40}Ca and ^{40}Ca + ^{48}Ca, compared in an energy scale relative to the Coulomb barrier. Right: Barrier distributions for the same three systems.

the experimental BD. However, by including also the octupole excitations that good agreement is lost, even if a couple of oscillations can be seen above the main peak of the BD. The present comparison with the CC results would tell us that, while the effect of transfer is surely large, the evidence of an *elastic* transfer coupling is not clear at all in ^{42}Ca + ^{40}Ca. We should not forget that the expression of the 2n form factor is very rough, and its coupling strength is arbitrary in our calculations to a large extent.

A final remark: when comparing the BD of the three systems ^{42}Ca + ^{40}Ca, ^{40}Ca + ^{40}Ca [9] and ^{40}Ca + ^{48}Ca [10] (Fig. 6, right panel), the two asymmetric cases are not so different from each other. These are the two cases when transfer couplings play an important role, no matter whether the Q-values are zero or not. The corresponding excitation functions are reported in the left panel of the same Figure.

5 Summary

We have measured the near- and sub-barrier fusion excitation function of ^{42}Ca + ^{40}Ca, where no previous data on the fusion cross sections existed sofar. The energy step and the statistical errors of the measurements were small enough to allow extracting the fusion barrier distribution with good accuracy. This barrier distribution clearly shows a double-peak structure which is tempting to associate with the elastic 2n-transfer, since it is known that any coupling to a zero Q-value channel should produce a symmetric barrier distribution with two equal peaks on either side of the uncoupled barrier.

When comparing the present data with simple CC calculations, we find that the octupole vibrations (very strong in ^{40}Ca, but rather high in energy) do not essentially influence the shape of the barrier distribution if no transfer coupling is considered. However, the simple two-peak structure is lost in the more complete calculations where the quadrupole modes, the octupole vibrations *and* the 2n transfer are included. The CC predictions presented in this contribution are based only on a schematic (approximate) formulation of the 2n transfer form-factor. While keeping this in mind, we may conclude that transfer couplings are important in ^{42}Ca + ^{40}Ca, but the evidence of an elastic two-neutron transfer is sofar marginal.

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