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

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Several measurements exploited the concept of a fusion barrier distribution, to identify the nature of couplings responsible for cross section enhancements.

- Double-closed shell
- Several phonon couplings
- Prolate deformation
- Exadecapole deformation $\beta_4 < 0$
- Target phonon state
- Complex surface vibrations

... but identifying the effect of coupling to transfer channels has often been elusive, when deduced from comparing with calculations.

**Coupling to transfer** is clear only in the cases where the experimental evidence is conclusive in itself.
Transfer couplings in the Ca + Zr systems

no energy shifts

shifted according to Akyüz-Winther

shifted according to phonon couplings
A striking fusion barrier distribution is predicted for strong coupling to a single channel with zero Q-value.

One expects a roughly symmetric distribution with two peaks, one on each side of the original uncoupled Coulomb barrier.
Simultaneous and sequential transfer with $Q=0$

(model calculations using the code FRESCO)

Two peaks for any number of simultaneous transfer channels

The number of peaks is equal to the number of channels

The investigation of $^{58}$Ni+$^{60}$Ni was performed to evidence the coupling to the 2-neutron elastic transfer channel...

...but the barrier distribution with several well-defined peaks could only be explained by multi-phonon couplings!

The effect of 2n elastic transfer was found to be relatively unimportant.
The barrier distribution of $^{58}\text{Ni} + ^{54}\text{Fe}$

The complex structure closely resembles the BD of $^{58}\text{Ni} + ^{60}\text{Ni}$, and it is nicely reproduced by CC calculations.

The fusion dynamics is dominated by low-energy surface modes.

Little space is left for the possible influence of the alpha-elastic transfer.
A two-peak distribution in $^{28}\text{Si} + ^{24}\text{Mg}$, as the consequence of elastic alpha transfer?


Data from A. Morsad et al., PRC 41, 988 (1990)

A clear case of a symmetric distribution with two peaks has never been observed, probably because low-lying surface vibrations have a dominant role in most systems.
Strong transfer couplings produce a wide and flat barrier distribution, even if $Q \neq 0$.

Fusion barrier distributions of $^{32,36}S + ^{48}Ca$

G. Montagnoli et al., PRC 87, 014611 (2013)
We decided to investigate the case of $^{42}\text{Ca} + ^{40}\text{Ca}$

the chance to observe a two-peak B(E) largely depends on the coupling strength of the 2n elastic transfer, which is actually unknown.

- CC calculations including the quadrupole mode of $^{42}\text{Ca}$, and the 2-neutron elastic transfer channel.
- do the high-energy 3$^+$ states simply renormalize the potential and "rigidly" shift the B(E)?
The electrostatic beam deflector and the detector telescope at LNL

- HV
+ HV
beam
target
degraded beam
fusion on C, F

\( ^{42}\text{Ca} + ^{40}\text{Ca} \)

(lowest measurable cross section \(\approx 0.5-1 \mu\text{b} \))
The measured fusion excitation function

\[ \sigma \text{ (mb)} \]

\[ E_{\text{c.m.}} \text{ (MeV)} \]

\[ ^{42}\text{Ca} + ^{40}\text{Ca} \]
The measured fusion excitation function compared to CC calculations

Woods-Saxon potential

\[ V_0 = 88.71 \text{ MeV} \]
\[ r_0 = 1.14 \text{ fm} \]
\[ a = 0.65 \text{ fm} \]

This gives a barrier

\[ V_b = 54.4 \text{ MeV} \]
\[ R_b = 9.85 \text{ fm} \]

(very near to the Akyüz Winther barrier)
The low-lying structure of $^{40}\text{Ca}$ and $^{42}\text{Ca}$

The two neutrons of $^{42}\text{Ca}$ occupy the $1f_{7/2}$ and $2p_{3/2}$ shells above the magic numbers $Z=N=20$

<table>
<thead>
<tr>
<th></th>
<th>$I^\pi$</th>
<th>$E_x$(MeV)</th>
<th>$\beta_C$</th>
<th>$\beta_N$</th>
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<tbody>
<tr>
<td>$^{40}\text{Ca}$</td>
<td>2+</td>
<td>3.905</td>
<td>0.12</td>
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<td>3-</td>
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<tr>
<td></td>
<td>3-</td>
<td>3.447</td>
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<td>0.16</td>
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</tbody>
</table>
The schematic two-neutron transfer form-factor

The effect of two-nucleon pair-transfer is simulated by the form factor

\[ F_t(r) = -\sigma_t \frac{dU(r)}{dr} \]

where the strength \( \sigma_t \) of the pair transfer is treated as an adjustable parameter.
In this case we have used \( \sigma_t = 0.39 \text{ fm} \) best fitting the existing fusion data on \(^{40}\text{Ca} + ^{48}\text{Ca}\).
The Q-value is taken as zero, obviously, for the elastic transfer.

Barrier distributions and coupled-channel calculations

Coupling to octupole vibrations “complicate” the picture!
Comparison of excitation functions

\[ \sigma_{\text{fus}} (\text{mb}) \]

\[ E/V_b \]

- \( ^{40}\text{Ca} + ^{40}\text{Ca} \)
- \( ^{42}\text{Ca} + ^{40}\text{Ca} \)
- \( ^{40}\text{Ca} + ^{48}\text{Ca} \)

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Barrier distributions in several Ca + Ca systems

\[ \frac{1}{\pi R_b^2} \frac{d^2}{dE^2} \frac{E_\sigma}{dE} \quad [\text{MeV}^{-1}] \]

\[ E_{\text{c.m.}} \quad (\text{MeV}) \]
Summary

• We have measured the near- and sub-barrier fusion excitation function of $^{42}\text{Ca} + ^{40}\text{Ca}$, where no previous data on the fusion cross sections existed.

• The energy step and the statistical errors of the measurements are small enough to allow extracting the barrier distribution BD with good accuracy.

• The observed BD clearly shows a double-peak structure, and it is tempting to associate this feature with the elastic 2n-transfer.

• The octupole vibrations (very strong in $^{40}\text{Ca}$) do not essentially influence the shape of the barrier distribution if no transfer coupling is considered. The simple two-peak structure is lost when the 2n transfer is additionally included.

• Transfer couplings are important in $^{42}\text{Ca} + ^{40}\text{Ca}$, but the evidence of an elastic two-neutron transfer is marginal. CC predictions are based only on a schematic (approximate) formulation of the 2n transfer form-factor.