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Fusion of ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca and ^{48}Ca + ^{48}Ca

G.Montagnoli[1,a] and A.M.Stefanini[2]

[1] Dipartimento di Fisica, Università di Padova, and INFN, Sezione di Padova, I-35131 Padova, Italy
[2] INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro (Padova), Italy

Abstract. The recent experiment on fusion of ^{40}Ca + ^{40}Ca is described in some detail and the results are reported. A full excitation function has been measured from well above the Coulomb barrier, down to low energies where the cross section reduces to ≃20 μb. A comparison is done with the recently published data on fusion of ^{40}Ca + ^{48}Ca and of ^{48}Ca + ^{48}Ca. The trends are different, in particular as far as the logarithmic derivatives (slopes) are concerned, in the interesting energy region below the barrier. The slope for systems where ^{40}Ca is involved, show a characteristic behavior with a tendency to saturate in a limited energy range just below the main barrier. The slopes resume increasing at lower energies, possibly indicating the influence of nuclear structure (the strong octupole vibration of ^{40}Ca) at such low energies, together with the clear presence of the fusion hindrance phenomenon. The results of coupled-channels calculations are presented.

1 Introduction

The interest in studying fusion of various combinations of calcium isotopes dates back to the early 80's [1], when the freshly discovered phenomenon of "fusion enhancement" below the Coulomb barrier prompted various groups to study different behaviors in several cases. The magic nature of ^{40}Ca and ^{48}Ca immediately attracted the interest of both experimentalists and theoreticians [2]. Fusion of ^{40,48}Ca + ^{48}Ca was investigated again later on [3] with the goal of extracting fusion barrier distributions [4] from accurate measurements of the excitation functions [5].

A renewed interest has been developed in the last few years, in the context of what is generally known as the fusion hindrance effect at far sub-barrier energies [6–8]. Fusion cross sections for the system ^{40}Ca + ^{40}Ca have been recently measured at Legnaro in a wide energy range down to very low energies. This experiment completes the study of the Ca+Ca systems (the results concerning ^{40,48}Ca + ^{48}Ca were recently published [9, 10]). In fact, the three systems are an ideal set of cases where the possible influence of neutron excess and/or nuclear structure on fusion hindrance can be investigated. Here we would like to show the result of the recent measurements on ^{40}Ca + ^{40}Ca, and to point out similarities and differences when comparing with ^{40}Ca + ^{48}Ca and ^{48}Ca + ^{48}Ca.

2 Experiment and Results

The most recent measurements have been performed for the system ^{40}Ca + ^{40}Ca at the XTU Tandem of LNL, using ^{40}Ca beam currents up to ≃8-10 pnA and thin (∼ 50μg/cm^2)

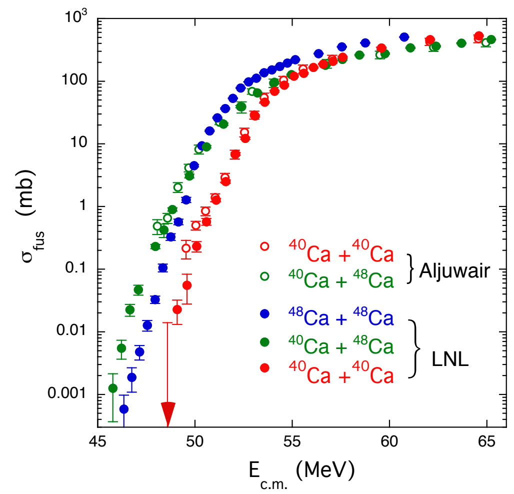

Fig. 1. Fusion excitation function of ^{40}Ca + ^{40}Ca and of other Ca+Ca systems, measured in recent LNL experiments and in the previous one by Aljuwair et al. [1]. The upper limit obtained for the lowest energy point of ^{40}Ca + ^{40}Ca is marked by an arrow.

$^{40}CaF_2$ targets on 15μg/cm^{2}carbon backings. The ^{40}Ca target isotopic enrichment was very high (99.96%). Even with this high enrichment, the lowest measurable cross section resulted to be around 20 μb, as we will see, due to the presence of small quantities of $^{42,43,(44)}$Ca for which the Coulomb barriers in the laboratory system are significantly lower than for ^{40}Ca. Heavier Ca isotopes (mainly ^{48}Ca), although present, were of minor importance since their fusion evaporation products could be separated out thanks to the mass identification of the detector set-up.

The evaporation residues (ER) have been detected near 0^o separating out the beam and beam-like particles by an electrostatic filter, already used for several sub-barrier fu-

[a] e-mail: giovanna.montagnoli@pd.infn.it

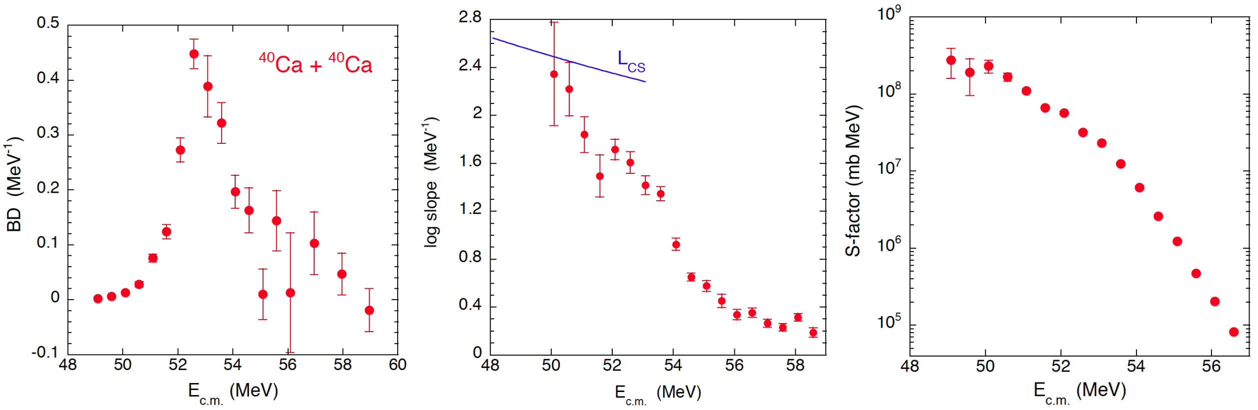

Fig. 2. (left) Barrier distribution derived from the present data for ^{40}Ca + ^{40}Ca. (center) Logarithmic derivative (slope) d[ln(Eσ)]/dE of the excitation function. The line marked L_{CS} is the slope expected for a constant S factor vs. energy. (right) The astrophysical S factor showing a tendency to develop a maximum around E≃49 MeV.

sion measurements at LNL, in its recently upgraded configuration. A scheme of the detector set-up downstream the filter, can be found in Ref. [11]. It is composed of two micro-channel plate detectors, a ionization chamber for ΔE measurement, and a final 600 mm^2 silicon detector giving the residual energy, and the start signal for the two independent time-of-flights. The effective solid angle of the complete set-up is ≃ 0.045 msr. The ER angular distribution was measured at a representative energy (E_{lab}= 109 MeV) near the barrier. The measured fusion excitation function is shown in Fig. 1, where the reported errors are purely statistical. The absolute cross section scale is accurate to within ± 7-8%. The measured cross sections agree with the results of a previous experiment [1] (also plotted), and extend further down in energy; we can note that a smoother trend is observed below the barrier.

The fusion barrier distribution (BD) extracted from the present data with the usual three-point formula and an energy step of ≃1.5 MeV, is shown in the left panel of Fig. 2. BD is normalized to πR_b^2, where R_b is the barrier radius resulting from the Akyuz-Winther potential [12]. One main peak dominates the distribution, as recently observed for ^{48}Ca + ^{48}Ca [9]. Above that peak, one cannot exclude the presence of a smaller structure around 57 MeV, whose nature, if real, deserves further investigation [13]. The logarithmic derivative of the excitation function is reported in Fig. 2 (center). It is obtained as the incremental ratio for pairs of points, with energy steps of 1 MeV. One sees a kind of saturation, or an irregularity, with decreasing energy just below the barrier. At the lowest energies the slope seems to increase again, even if the errors are quite large, and gets very near to the value L_{CS} expected for a constant astrophysical S-factor. Correspondingly, the S-factor (Fig. 2, right) gives the impression to reach a maximum vs. energy at E≈49 MeV.

3 Near-by Ca + Ca Systems

The full measured excitation functions of ^{40}Ca + ^{40,48}Ca and of ^{48}Ca + ^{48}Ca are reported in Fig.1. It is a pity that fusion cross sections for ^{40}Ca + ^{40}Ca could not be measured below ≈ 20 μb, due to the target impurities. In Fig.1, it is hard to observe possible differences in the relative trends. Then we plot again the data (but only the recent data, and near and below the barriers) in Fig.3, where the energy scale has been reduced according to the Akyüz-Winther (AW) [12] estimate of the barrier V_b. The cross section scale is not reduced, since the small differences of the barrier radius among the three cases are negligible for the present overall comparison. ^{48}Ca + ^{48}Ca has the lowest cross sections in the region near the barrier, relevant for coupling effects, since ^{48}Ca is more stiff than ^{40}Ca and, in particular, does not possess the strong octupole vibration of ^{40}Ca. Alternatively, one can say that the AW parametrization is not adequate. Indeed, this has been designed to reproduce the average behaviour of the nuclear potential with varying mass and Z numbers. One should not, however, expect to reproduce local isotopic variations associated to strong phonons.

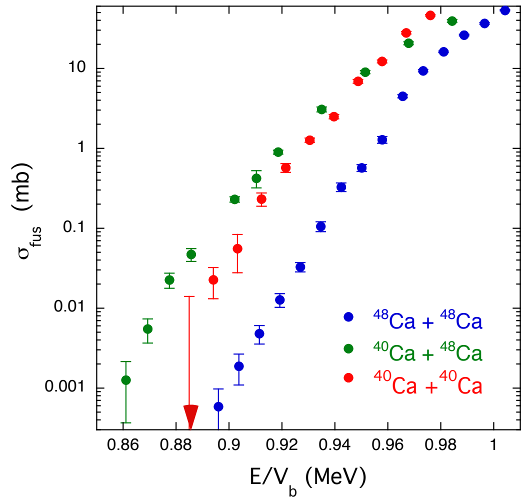

Fig. 3. Fusion excitation function of ^{40}Ca + ^{40}Ca and of other Ca+Ca systems [9, 10].

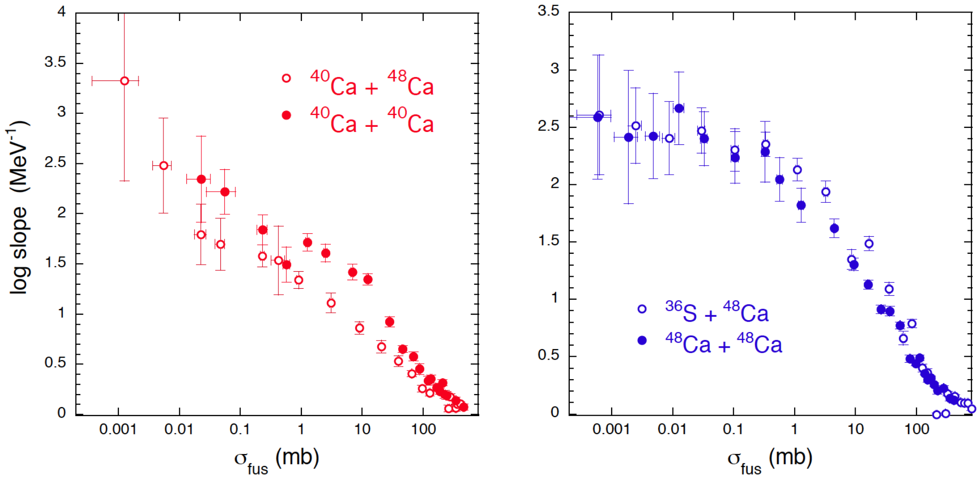

Fig. 4. (left panel) Logarithmic derivative of two systems involving ^{40}Ca, and (right panel) not involving ^{40}Ca. The slopes are plotted vs. measured fusion cross sections only for ease of comparison among the different cases having different Coulomb barriers.

Anyway, ^{40}Ca + ^{40}Ca has larger cross sections in this representation, and ^{40}Ca + ^{48}Ca receives an "extra-bonus" probably due to couplings to the many transfer channels with positive Q-values available for this system [2, 10]. But let us observe in more detail what happens much below the barrier. Fig.3 does not help us much in this sense, although a careful observation allows one to appreciate that the cross sections for two cases involving ^{40}Ca start dropping down fast at the lowest energies.

A representation with the logarithmic derivative of the excitation functions is by far more illuminating. This is done in two panels of Fig.4, separately for the two cases with ^{40}Ca (left), and for ^{48}Ca + ^{48}Ca (right). Here the data derived from the recent measurements on ^{36}S + ^{48}Ca [14] have been added, since ^{36}S is rather stiff and neutron-rich, as ^{48}Ca. Fig.4 (left panel) indicates that the slopes for the two cases with ^{40}Ca show a tendency to saturate just below the main barrier, and then increase again for lower energies (cross sections). Where ^{48}Ca is involved (right panel), the logarithmic slope clearly saturates and remains saturated down to very small energies (cross sections).

What is the reason for this different behavior ? There is the possibility that the strength of the octupole vibration of ^{40}Ca comes into play and produces that slope irregularity. This was suggested by N.Rowley [13] recently, when the present data on ^{40}Ca + ^{40}Ca were not yet available, and seem to find an interesting confirmation here.

Additionally, the present observations show once again that the representation in terms of the logarithmic derivative of the excitation function is much more sensitive than the barrier distribution to small details far below the barrier. In the μb cross section range, nothing is visible from the barrier distributions itself (see Fig.2 for example), but multi-phonon excitations of strong modes may still produce barriers with small "weights", speaking in the eigenchannel representation. We are able to reveal small effects of nuclear structure down to very low energies.

It is probably worthwhile to recall a few "prophetic" words from the talk of C.Dasso at the Fusion97 Workshop [15] in Canberra, when discussing the method of extracting fusion barrier distributions from the excitation function, and its real significance: "... if a function is very rapidly changing it is far better to interpolate its logarithm ..." and again "... if one is interested in magnifying features of the excitation function, there is no compelling reason to use, in particular, the second energy derivative of (Eσ) ...".

4 Coupled-channels Analyses

In order to investigate further the possible effect of (multiple) 3^- excitations on low-energy fusion cross sections of Ca+Ca systems, we have performed simple coupled-channels (CC) calculations using the code CCFULL [16], modified for symmetric systems [17]. This was done for the two cases ^{40}Ca + ^{40}Ca and ^{48}Ca + ^{48}Ca, neglecting in either case the possible role of quadrupole vibrations, weak anyway. We stress that the calculations presented here below, "a priori" do not pretend to reproduce the data, but simply to check whether the main trends we observed from a purely experimental point of view (see Sect.3) below the barrier, might be actually due to the large difference in octupole strength that is known to exist between the two calcium isotopes.

The ion-ion potential we used is essentially the AW potential [12], with minor modifications of the well depth so to fit qualitatively the excitation function near the barrier (in the vicinity of 50–100 mb). We used β_3=0.41 (E_x=3.737 MeV) for ^{40}Ca, and β_3=0.23 (E_x=4.507 MeV) for ^{48}Ca [18]. The results are plotted in Fig.5 (left panels), both cross sections and slopes are reported there, resulting when either only one 3^- state is included or when two octupole phonons are considered ($(3^-)^2$ means one phonon for each colliding nucleus). For reference, we show, in the two right panels of Fig.5 the experimental and calculated slopes again, but we have replaced the fusion excitation functions with the experimental and calculated barrier distributions, for the two systems.

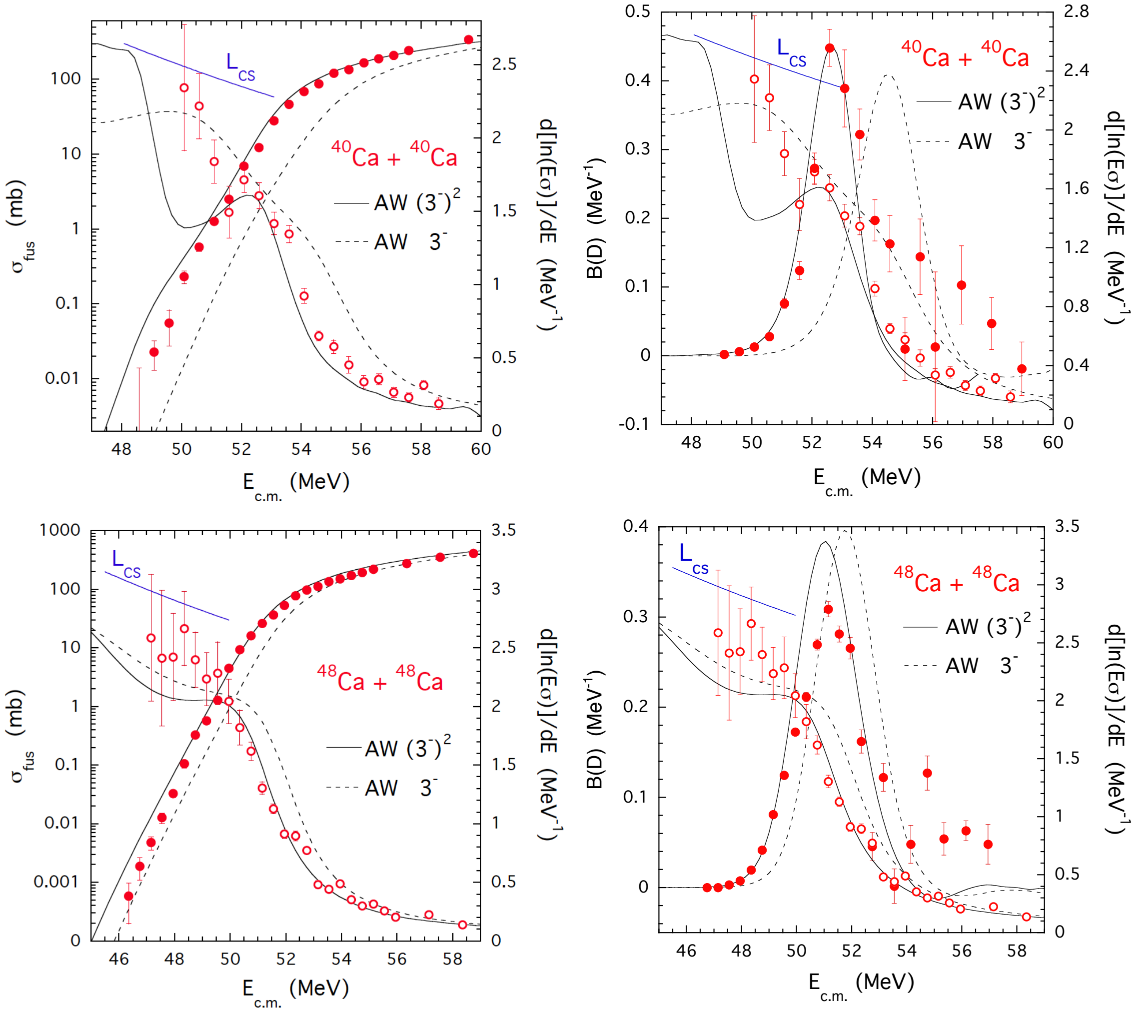

Fig. 5. (left panels) Fusion excitation function (full symbols, left scale) and logarithmic slopes (open symbols, right scale) of ^{40}Ca + ^{40}Ca and ^{48}Ca + ^{48}Ca, compared with simplified CC calculations (see text). (right panels) The two barrier distributions (full symbols, left scale)) extracted from the experimental data and resulting from CCFULL, together with the measured and calculated logarithmic slopes.

The calculations with two octupole phonons ($(3^-)^2$), overall, overestimate the low-energy cross sections for both systems. This is expected, since fusion hindrance is there, and we are using a standard Woods-Saxon potential that is known to be inadequate to describe such a phenomenon. Moreover, it is easy to recognize the larger calculated effect of the second phonon in ^{40}Ca + ^{40}Ca in terms of a global "fusion enhancement". But the point is another one.

Where the octupole is weak (^{48}Ca + ^{48}Ca), the two predicted slopes are similar and rather flat below the main barrier, according to the data trend. The second phonon does not change the situation, at least down to ≈45 MeV, where the fusion cross section should be ≈10 nb. Where the octupole is strong (^{40}Ca + ^{40}Ca) the effect of the second 3^- on the low-energy slope is calculated to be radical, and a marked rise up appears at low energies. It is worth pointing out that it is hard (not impossible) to obtain experimental data at very low energies, and even the CCFULL results may be not so reliable in that energy range, even if we are not using a shallow potential.

Nevertheless, the calculated trends are indeed what the data qualitatively indicate. Obviously, the slope rise up for ^{40}Ca + ^{40}Ca is predicted to appear too low in energy in this simplified approach. The different behaviors of ^{40}Ca + ^{40}Ca and ^{48}Ca + ^{48}Ca below the barrier are only evident when observing their logarithmic derivatives, while the calculated barrier distributions are structureless at low energies, and reproduce both data sets reasonably well.

All this needs of course support (or confutation) from more complete CC calculations based on models properly taking into account the hindrance effect, based e.g. on the shallow potentials resulting from the M3Y + repulsion interaction recently introduced [19]. Complete results have already been reported for ^{48}Ca + ^{48}Ca [20]. Very recently, calculations have been performed within the same approach also for ^{40}Ca + ^{40}Ca [21]. Fig.6 shows the various potentials used (upper panel) and the resulting fusion excitation functions compared with experiment (lower panel) [21]. One sees that a good fit to the data is reached by the use of a shallow potential.

5 Summary

The fusion excitation function for the system ^{40}Ca + ^{40}Ca has been measured in a wide energy range covering the deep sub-barrier region where the fusion hindrance phenomenon was reported in the past few years. This experiment completes the study of the Ca+Ca systems (the results concerning ^{40,48}Ca + ^{48}Ca were recently published). The measured fusion excitation function extends the results of a previous experiment [1] down to $\simeq 20\mu$b. The two sets of data agree, however, a smoother trend is observed in the present experiment below the barrier.

The fusion barrier distribution shows only one main peak. The presence of a smaller structure at an higher energy cannot be excluded. The logarithmic derivative of the excitation function increases with decreasing energy and shows a tendency to flatten out just below the main barrier. At the lowest energies, however, the slope increases again.

A detailed comparison of excitation functions and corresponding slopes has been performed between the three systems ^{40}Ca + ^{40}Ca, ^{40}Ca + ^{48}Ca and ^{48}Ca + ^{48}Ca. This indicates different trends of the logarithmic derivatives according to whether ^{40}Ca participates or not in the reaction. We have suggested that this may be due to the strong 3^- vibration of ^{40}Ca (the corresponding mode is much weaker in ^{48}Ca). This hypothesis is strengthened by the results of simplified CC calculations for the two symmetric systems ^{40}Ca + ^{40}Ca and ^{48}Ca + ^{48}Ca, in particular when the simultaneous (mutual) one-octupole-phonon excitation in each nucleus is taken into account.

The present data on ^{40}Ca + ^{40}Ca are being fully analyzed within the coupled-channels model, using both a standard Woods-Saxon potential and the M3Y + repulsion (shallow) potential.

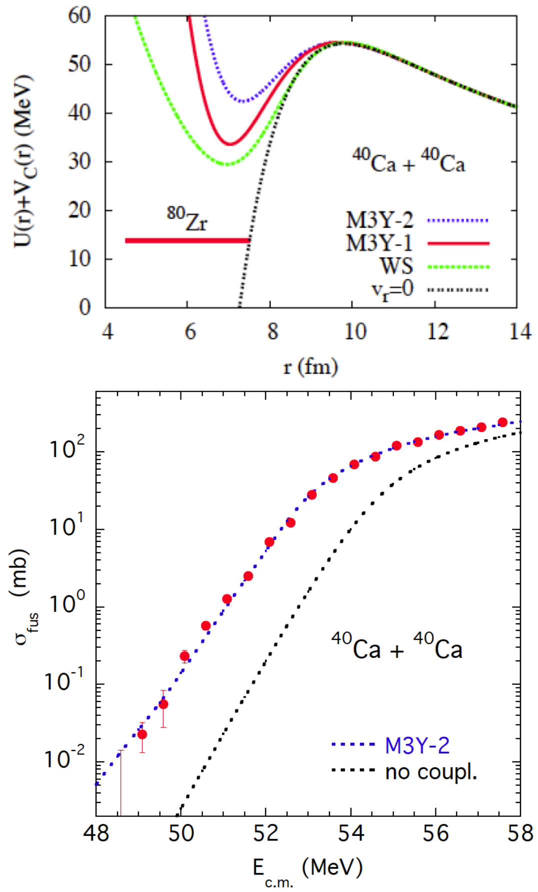

Fig. 6. Entrance channel potentials (upper panel), and fusion cross sections for ^{40}Ca + ^{40}Ca, compared with data, calculated with the M3Y-2 + repulsion potential [21]. These results will be used to calibrate detailed calculations for ^{40}Ca + ^{48}Ca [10].

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