Fusion of calcium isotopes and of other medium mass systems

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Abstract.
Heavy-ion fusion below the barrier displays interesting, and sometimes unexpected, features. Several different facets of the fusion hindrance phenomenon have been evidenced in the last few years. Very recent data on $^{40,48}$Ca + $^{40,48}$Ca are presented and discussed in this paper. In all cases a hindrance of fusion far below the barrier has been observed. Coupled-channel effects (producing barrier distributions) influence the threshold energy for hindrance. The excitation functions of the two symmetric systems are similar, while the case of $^{40}$Ca + $^{48}$Ca is quite different both above and below the barrier, possibly due to couplings to transfer channels with positive Q-values. Other systems in the same mass region show different trends that have to be related to the nuclear structure of the colliding nuclei. Investigating the behavior of lighter systems will be interesting also from the astrophysical point of view.

1. Introduction
The study of heavy-ion fusion dynamics in the region near and below the Coulomb barrier has produced a large amount of experimental data and theoretical analyses in recent years, in particular for medium-mass systems [1] (for a recent overview on this subject see the Proceedings of the Fusion11 Conference [2]). Couplings to low-lying collective modes of the colliding nuclei and, in several cases, to nucleon transfer channels enhance fusion cross sections close to the barrier. For medium-heavy nuclei multi-phonon excitations have been shown [3] to become important, leading to complex fusion barrier distributions with discrete structures [4, 5].

The behavior of the experimental excitation function at lower energies, with respect to coupled-channel (CC) calculations employing standard ion-ion potentials, is determined by the relatively smaller effects of those couplings and by the intervening so-called ”hindrance” phenomenon [6, 7, 8, 9] i.e. a sharp decrease of the cross sections with decreasing energy, well below the CC predictions.

Hindrance shows up as a common feature of sub-barrier heavy-ion fusion reactions, because it seems to be originated, roughly speaking, by our incomplete knowledge of the ion-ion potential at radial distances corresponding to the inner side of the Coulomb barrier. Fusion barrier distributions [4, 10] $BD(E)$ and logarithmic derivatives (slopes) $L(E) = d[ln(E\sigma)]/dE$ of the excitation functions are convenient representations of these effects in different energy ranges. Actually, it is straightforward to show that a simple relation holds [6] between these two quantities $BD(E)$ and $L(E)$, that is,
While the barrier distribution BD is of great help in identifying the nature and strengths of couplings near the barrier, the trend of the logarithmic derivative $L(E)$ turns out to be a more sensitive tool for the analysis of fusion dynamics at deep sub-barrier energies. This is so because (see Eq. (1)) possible irregularities of the low-energy slope are hidden in the barrier distribution by the term $L(E)^2$ and the overall factor $\sigma E$.

It is also useful and significant to consider the astrophysical S factor. This is defined as $S(E) = \sigma E \exp(2\pi\eta)$ [11], where $E$ is the center-of-mass energy and $\eta = Z_1 Z_2 e^2 / (\hbar v)$ is the Sommerfeld parameter. The slope expected for a constant S factor is $L_{CS}(E) = \pi \eta / E$, as shown in Ref. [12].

It has been noticed that if the hindrance effect is strong enough, the experimental $L(E)$ will get as large as $L_{CS}(E)$, and possibly overcome that value. When $L(E) = L_{CS}(E)$ a maximum of $S(E)$ is generated, and the corresponding energy is phenomenologically taken as the threshold of hindrance. This usually nicely agrees with the more general (but model-dependent) definition that identifies the threshold as the energy where the experimental cross sections start falling below the CC results, with decreasing energy.

All this has a prospective interest also for nuclear astrophysics, because cross sections (reaction rates) of fusion reactions between light or neutron-rich heavy ions at extremely low energies are very important in both hydrostatic and explosive stellar burning processes, and in the evolution of accreting neutron stars [13]. This paper is a short review of these topics, with particular emphasis to the recent data our group has obtained for the excitation functions of various systems involving calcium isotopes. Comparisons with CC calculations and with the behavior of near-by cases will be presented as well.

2. The $^{40,48}$Ca + $^{40,48}$Ca systems

The study of near- and sub-barrier fusion of calcium isotopes has a long background with several steps. Early experiments dealt with the $^{40,44,48}$Ca systems [14] with the aim of studying the enhancement of cross sections caused by inelastic and transfer couplings in the different cases [15]. The motivation came from the double closed-shell structure of $^{40}$Ca and $^{48}$Ca. Differences from the case with $^{44}$Ca were searched for, as well as clues of coupling to transfer channels with positive Q-values in $^{40}$Ca + $^{48}$Ca. Clear evidences of these effects came from the coupled-channel analysis of Ref. [16].

Fusion barrier distributions were extracted some years later for the two systems $^{40,48}$Ca + $^{48}$Ca [17] from accurate measurements of the excitation functions, and detailed effects of the octupole phonons of both calcium isotopes were suggested in a more recent study [18] by N.Rowley and K.Hagino. In the last few years, our collaboration has extended the measurements of excitation functions down to very low energies, for the three cases $^{48}$Ca + $^{48}$Ca [19], $^{40}$Ca + $^{48}$Ca [20] and $^{40}$Ca + $^{40}$Ca [1]. Our purpose has been to obtain detailed experimental information on the fusion hindrance behaviour in these systems having different nuclear structure, varying Q-values for fusion and for nucleon transfer channels, and quite dissimilar neutron excesses.

3. Recent experiments

The experiments for the Ca+Ca systems have been performed at the XTU Tandem accelerator of the INFN - Laboratori Nazionali di Legnaro (LNL) using $^{40,48}$Ca beams with intensities up to $\simeq 10$ pnA. The evaporation residues (ER) were detected near $0^\circ$ separating out the beam and beam-like particles by an electrostatic filter, already used for several sub-barrier fusion measurements at LNL [21], in its recently upgraded configuration. Details about the filter, as well as a scheme of the detectors downstream, can be found in Ref. [22].
Figure 1. (left) Fusion excitation functions of Ca+Ca systems, recently measured at LNL. The insert shows the low-energy cross sections, where the energy scale is normalized to the barrier resulting from the Akyüz-Winther (AW) potential [24]. Here the cross sections are not corrected for the differences of barrier radii, because the resulting variations are small compared to the overall trends we are discussing here. (right) Logarithmic derivatives of the excitation functions, see text. The continuous lines are the corresponding $L_{CS}(E)$ values.

The measured fusion excitation functions of the three different calcium isotope combinations are reported in Fig. 1 (left panel). The recent article of Montagnoli et al. [1] is a comprehensive report of these experiments. The cross sections agree with previous experimental results [14, 17] in the common energy ranges. The excitation functions of the two symmetric cases $^{48}$Ca + $^{48}$Ca and $^{40}$Ca + $^{40}$Ca are similar to each other, with a tendency of the heavier one to have a steeper slope below the barrier. The behavior of the three systems at low energies is clearly observable in the insert of the figure.

At a first glance, the most striking feature is that the cross sections for the asymmetric system $^{40}$Ca + $^{48}$Ca [20] exceed the data for the other two [19] at low energies, while they are definitely smaller above the barrier. This may be an indication of the influence of couplings to transfer channels with positive Q-values in the fusion of the asymmetric system, as it will be shown also by the results of CC calculations, later in this paper. This reminds of the relative trend of the three $^{58}$Ni + $^{58}$Ni, $^{58}$Ni + $^{64}$Ni and $^{64}$Ni + $^{64}$Ni cases, observed in the pioneering work of Beckerman et al. [23].

The logarithmic derivatives of the excitation functions are reported in the right panel of Fig. 1. They were simply obtained as the incremental ratios for pairs of experimental points, with energy steps $\approx$1-1.5 MeV, depending on the system. The hindrance sets in for $^{40}$Ca + $^{48}$Ca, in spite of the large enhancement in the fusion of this system near the barrier, and the threshold is marked by the sharp increase of the slope $L(E)$ at $\approx$47 MeV, where the cross section is already very small, not more than a few $\mu$b. One may qualitatively suppose that transfer couplings (enhancing fusion) ”allow” hindrance to show up only at very small energies.

By only observing the trend of the slopes in Fig. 1, it is not obvious that fusion is hindered for the other two cases, in the whole measured energy range. We have to consider the experimental cross sections with respect to CC calculations based on a standard Woods-Saxon potential.
Figure 2. Fusion excitation functions of $^{40}$Ca + $^{40}$Ca (left) and of $^{48}$Ca + $^{48}$Ca (right) compared with CCFULL calculations (see text).

Figure 3. Fusion barrier distributions $BD(E)$ of $^{40}$Ca + $^{40}$Ca, $^{40}$Ca + $^{48}$Ca and $^{48}$Ca + $^{48}$Ca. Three arrows are drawn at the energy thresholds of hindrance, see text. The $BD(E)$ have been extracted with the usual three-point formula and energy steps of $\approx$1.5 MeV. They are normalized to $\pi R_b^2$, and $R_b$ is the barrier radius resulting from the AW potential [24].

This is done in Fig. 2, where the calculations have been performed with CCFULL [25] using the modified AW potentials of the original articles [9, 19], and including the lowest $2^+$ and $3^-$ excitations of both colliding nuclei.

The CC predictions overestimate the experimental excitation functions below some energy. So hindrance does occur, but the effect is not so strong to increase the slope up to the $L_{CS}(E)$ value (and consequently to produce a maximum of the S-factor). In these two cases we identify the thresholds of hindrance (marked with arrows) with the energies where the data fall below the calculations.

Next, we consider the fusion barrier distributions for the three Ca+Ca systems, also in relation to the hindrance thresholds. For the two symmetric systems one main peak dominates the distributions, as expected because the lowest $2^+$ and $3^-$ states are high-energy excitations ($\approx$4 MeV or higher) in these magic nuclei. Smaller structures may exist a few MeV above the main peak in both cases, but the errors are rather large over there. On the contrary, a
tail extending towards low energies shows up for $^{40}\text{Ca}+^{48}\text{Ca}$. This is a further signal of the importance of transfer couplings with positive $Q$-values in this system. Vertical arrows mark the hindrance thresholds mentioned above, in Fig. 3. In all cases, hindrance shows up when coupling effects get small enough, that is, around the energy where the BD vanishes. In the case of $^{40}\text{Ca}+^{48}\text{Ca}$, in particular, the threshold is below the low-energy limit of the BD tail. As a conclusion of this Section, we can say that the three systems display sub-barrier hindrance with varying features, and it appears that its onset is pushed down to rather low energies for the asymmetric case, possibly due to transfer couplings. It is very interesting that nuclear structure effects can be revealed at energies so far below the Coulomb barrier.

4. Analysis with CC calculations

The phenomenon of fusion hindrance at far sub-barrier energies has been the object of various theoretical approaches. After the early suggestion of Dasso and Pollarolo [26] that hindrance offers the possibility to learn about the inner shape of the Coulomb barrier, the CC model of Refs. [27, 28] (M3Y + repulsion) has been very successful in reproducing the fusion data of several medium-mass systems. Esbensen and Mišicu proposed that a shallow pocket develops inside the barrier due to the saturation properties of nuclear matter, simulated by a repulsive core in the nuclear potential, so that the barrier is thicker with respect to what obtained e.g. with Woods-Saxon potentials. This suppresses fusion at low energies.

An alternative and interesting model was developed in Refs. [29, 30], where the dynamics of the two touching and overlapping nuclei is calculated at very low energies. The steep fall-off of cross sections below the threshold energy is attributed to the damping of the coupling potentials inside the touching point.

Very recently, also the role of quasi-fission at extreme sub-barrier energies has been emphasized [31], and a different approach has derived fusion barriers and cross sections from TDHF calculations [32].

The M3Y + repulsion model was applied to the $^{48}\text{Ca} + ^{48}\text{Ca}$ system [33]. The results of the analysis for all three Ca+Ca systems were published recently [1], and we refer to the original articles for details. The calculations make use of the M3Y+repulsion, double-folding potential which is described extensively in Refs. [27, 28]. The ion-ion potentials used for $^{40}\text{Ca} + ^{40}\text{Ca}$ and $^{48}\text{Ca} + ^{48}\text{Ca}$ are plotted in Fig. 4.

Figure 4. Entrance channel potentials for $^{40}\text{Ca} + ^{40}\text{Ca}$ (left) and for $^{48}\text{Ca} + ^{48}\text{Ca}$ (right). The red lines are the potentials used in the analyses of Refs. [1, 33]. The red horizontal bars are the energy locations of the ground states of the two compound nuclei.
The CC calculations [1] included couplings to low-lying excited states of projectile and target, i.e. the $2^+$, $3^−$, $5^−$, and all mutual excitations of these one-phonon states. The two-quadrupole-phonon excitations were also considered, by combining energies and adopted B(E2) values of the three members of the two-phonon multiplet into one effective two-phonon excitation. The two-phonon excitations of the $3^−$ and $5^−$ states were not considered, because no experimental information is available for those states. 24 channels were included in total.

Fig. 5 (left panel) reports the fusion excitation functions of the three Ca+Ca systems (as in Fig. 1) together with the results of the CC calculations using the M3Y + repulsion potential, which actually give a very good account of the data. Couplings to one- and two-nucleon transfer channels with $Q>0$ were also included in the case of $^{40}$Ca+$^{48}$Ca, using the same procedure of Ref. [16] fitting the older data of Aljuwair et al. [14]. There are several proton stripping and neutron pick-up channels with positive Q-values in this system, and also α-stripping has $Q>0$. One- and two-nucleon transfer couplings are essential to reproduce the very large cross sections below the barrier (see Ref. [1] for more details).

Furthermore, those couplings are needed at high energies. As a matter of fact, the suppression of the fusion cross sections for $^{40}$Ca+$^{48}$Ca at high energies is calculated to be due to transfer couplings. Without that, the calculation would fall more or less half-way between the two symmetric systems. This is best noticed in the linear plot of Fig. 5 (right panel) comparing the excitation functions for the three systems to the CC calculations.

A final observation: it is obvious from Fig. 5 that the slope below the barrier for $^{48}$Ca + $^{48}$Ca is steeper than the slope of the $^{40}$Ca + $^{40}$Ca. This is due to two concurring effects: 1) $^{40}$Ca is much softer than $^{48}$Ca, because its octupole excitation is somewhat lower in energy and much stronger; 2) the ion-ion potential giving the best fit for the lighter system (see Fig. 4) is not so shallow as the potential for $^{48}$Ca + $^{48}$Ca.

We also point out that an independent analysis of the $^{48}$Ca + $^{48}$Ca (and $^{36}$S + $^{48}$Ca [9]) data was carried out by Mišicu and Carstoiu [34] using shallow potentials, with good results.
5. Systematics of sub-barrier fusion in nearby systems

Measurements have been performed for several systems having projectile and target masses in the range $A \approx 30-60$. In some cases, similar behaviors have been observed below the barrier, and in particular far below the barrier. In other cases, the measured trends have been found to be quite different. Let us compare $^{36}\text{S} + ^{48}\text{Ca}$ [9] and $^{48}\text{Ca} + ^{48}\text{Ca}$ [19]. The two excitation functions decrease regularly down to the sub-µb level, showing a remarkably parallel behavior. This is shown in Fig. 6 (left panel). In more detail, the two logarithmic derivatives $L(E)$ (Fig. 6 (right panel)), after the sharp increase just below the Coulomb barrier, level off and become pretty constant with decreasing cross section (or energy).

5.1. Q-values and lighter systems

An interesting topic investigated in recent years has been whether systems with positive Q-value for compound nucleus formation display a maximum of the S-factor vs. energy or not. It is straightforward to show [7] that with $Q > 0$ a crossing between $L(E)$ and $L_{\text{CS}}(E)$ is not necessary, that is, the S-factor may not show any maximum at whichever energy. By the way, the Q-value is always positive in light systems and negative in medium-heavy and heavy ones.

Two recent experiments were performed for medium-light systems with $Q > 0$ with the aim of revealing their low-energy behavior. For the first case $^{28}\text{Si} + ^{30}\text{Si}$ [35] ($Q = +14.3$ MeV), the excitation function could be measured only down to $\approx 40$ µb, and a clear-cut conclusion on the existence of a maximum of S was difficult. Analogously, for the positive Q-value system $^{27}\text{Al} + ^{45}\text{Sc}$ [36], the cross sections drop much below the results of standard CC calculations, so that hindrance shows up, but no well defined evidence could be extracted for a maximum of the astrophysical S factor. A first indication of an S factor maximum in a system with positive Q-value has been obtained in the case of $^{40}\text{Ca} + ^{48}\text{Ca}$ discussed above [20]. For $^{36}\text{S} + ^{48}\text{Ca}$ ($Q = +7.6$ MeV), a steady decrease of the fusion cross sections is observed down to $\sigma_{\text{fus}} \approx 600$ nb, with no pronounced change of slope below the barrier (see Fig. 6 (right panel)). The logarithmic derivative saturates and does not reach $L_{\text{CS}}(E)$, as we commented above. The very similar behavior of $^{48}\text{Ca} + ^{48}\text{Ca}$, in spite of the fact that $Q$ has opposite signs.
for $^{36}\text{S} + ^{48}\text{Ca}$ and $^{48}\text{Ca} + ^{48}\text{Ca}$ (Q=+7.6 MeV and Q=–3.0 MeV, respectively), led to the conclusion that the sign of the Q-value is irrelevant, at least in the measured energy range.

### 5.2. Slightly heavier systems

It is interesting to note that in the (slightly) heavier systems $^{58}\text{Ni} + ^{58}\text{Ni}$ [37] and $^{64}\text{Ni} + ^{64}\text{Ni}$ [38] the logarithmic slopes keep increasing down to very low energies. The slopes reach and overcome the $L_{CS}(E)$ values (see Fig. 7). This prompted us to measure near- and sub-barrier fusion cross sections for the intermediate case $^{58}\text{Ni} + ^{54}\text{Fe}$ [22]. Here the low-energy quadrupole and octupole excitations have similar excitation energies and strengths for projectile and target. Thus the near-barrier excitation function is expected, and has been verified, to differ only slightly from the symmetric Ni+Ni systems [39].

As for the trend well below the barrier, $^{58}\text{Ni} + ^{54}\text{Fe}$ is similar to $^{58}\text{Ni} + ^{58}\text{Ni}$ (Fig. 7), and is quite different from what observed for $^{48}\text{Ca} + ^{48}\text{Ca}$ (and for $^{36}\text{S} + ^{48}\text{Ca}$, not plotted here) where the slope saturates below $L_{CS}$. As a matter of fact, rather than from the shape of the barrier distribution, the low-energy behavior of all these systems is best revealed by the logarithmic slope $L(E)$, as pointed out recently [40]. One faces the problem of disentangle the blend of reaction dynamics and nuclear structure producing these unsystematic behaviors, when comparing the slopes of Ni+Ni and lighter systems.

![Figure 7. Logarithmic derivatives of the excitation functions of $^{48}\text{Ca} + ^{48}\text{Ca}$, $^{58}\text{Ni} + ^{54}\text{Fe}$ and $^{58}\text{Ni} + ^{58}\text{Ni}$. The short black lines indicate the $L_{CS}(E)$ values, and the coloured lines are the results of CC calculations using WS potentials with very large diffuseness parameters $a=0.90$ fm.](image)

Let us look in more detail at the various features of $^{58}\text{Ni} + ^{54}\text{Fe}$ fusion. In Fig. 8 we can see that the excitation function (left panels) decreases very steeply at the lowest energies below $\approx 1$ mb. Here the data is compared with CCFULL calculations including 1- and 2-quadrupole-phonon excitations. The logarithmic slope keeps increasing, reaches and overcomes the $L_{CS}$ value. Consequently, $S$ shows a clear maximum as a function of the energy. The coloured lines are calculations using two different diffuseness parameters for the WS ion-ion potential.

### 5.3. Logarithmic derivatives and $S$ factors

Fig.9 reports the sub-barrier logarithmic derivatives for a number of systems, most of which have already been discussed in this paper. For reference, the full lines with different colours are the $L_{CS}$ values for the individual cases. The trends are disparate: crossing of $L_{CS}$ is observed for the heavier systems, but also for $^{40}\text{Ca} + ^{58}\text{Ca}$. Otherwise either $L(E)$ tends to saturate, or
stays very low, like in the case of $^{32}$S + $^{48}$Ca [41]. A few other systems have been measured, but they are not reported here for the sake of clarity. They are anyway plotted in the following figure of S-factors, where the situation is observed from another point of view.

The astrophysical S-factors for several systems (many of them have been investigated at LNL) are shown in Fig.10 for a final systematics. One notices that in some cases a maximum of $S$ when decreasing the energy is quite clear. In other cases it seems that one should perform further measurements at lower energies to have a clear-cut evidence, and for other systems (like e.g. $^{32}$S + $^{48}$Ca) the S-factor increases steadily with decreasing energy in the whole measured energy range. This may depend, qualitatively speaking, on varying nuclear structure situations, on more "collective" features like the neutron excess, on the Q-value for fusion, and probably on a combination of all these factors (and others), but are we able to perform reliable extrapolations for other systems where experimental data are missing? The current models (like the one based on the use of shallow potentials [27, 28]) indicate what is the underlying physics, but in our opinion we are far from a detailed and comprehensive understanding of sub-barrier fusion mechanisms, especially far below the barrier.

This is important not only for advancing our knowledge of nuclear physics, but it has also relevant consequences for nuclear astrophysics. Indeed, fusion reactions between lighter heavy ions are very important in both hydrostatic and explosive stellar burning processes. Reactions such as $^{12}$C + $^{12}$C, $^{12}$C + $^{16}$O and $^{16}$O + $^{16}$O are the main processes during the carbon and oxygen burning stages of massive stars. All of them have positive Q values for fusion. Other exotic fusion reactions, e.g. $^{24}$O + $^{24}$O, $^{28}$Ne + $^{28}$Ne and $^{34}$Ne + $^{34}$Ne, are involved in the evolution of the inner crust of neutron stars [13, 44] accreting under the influence of gravitation,
Figure 9. Logarithmic slopes of excitation functions for several heavy-ion systems. The data for $^{32}{\text{S}} + {^{48}{\text{Ca}}}$ are from Ref. [41].

and an evaluation of the relevant cross sections would be desirable. However, such experiments involving radioactive beams and targets are obviously not feasible in the laboratory.

If a maximum of the S factor develops as a consequence of hindrance, at very low energies the fusion cross sections and consequently the reaction rates in stars (or the timescale of different phases of stellar evolution) will be substantially lower than predicted by simple extrapolations of the trends at higher energies where sets of laboratory measurements already exist. Consequently, it is very important to measure the detailed low-energy behavior for similar medium-light systems, because the results will positively guide the extrapolation procedures for the astrophysical relevant reactions.

6. Summary
In this talk several aspects of heavy-ion fusion around and below the Coulomb barrier have been illustrated and discussed. A particular emphasis has been put on the fusion hindrance effect, with its varying features observed in medium-light systems. In fact, the very recent data obtained for the three combinations of calcium isotopes $^{48}{\text{Ca}} + {^{48}{\text{Ca}}}$, $^{40}{\text{Ca}} + {^{48}{\text{Ca}}}$ and $^{40}{\text{Ca}} + {^{40}{\text{Ca}}}$ have been presented. A hindrance of fusion far below the barrier has been observed in all three systems, and it has been observed that coupled-channel effects influence the threshold energy for hindrance in all cases.

The excitation functions of the two symmetric systems are similar, while the case of $^{40}{\text{Ca}} + {^{48}{\text{Ca}}}$ is quite different both above and below the barrier, with larger sub-barrier cross sections and a kind of fusion suppression at high energies. An analogous situation is found for the logarithmic derivatives of the excitation functions, where the slope of the asymmetric system is smaller, but increases sharply at the lowest measured energies. The barrier distributions are
Figure 10. Systematics of S factors for medium-light systems. The data for $^{28}\text{Si} + ^{64}\text{Ni}$ and $^{36}\text{S} + ^{64}\text{Ni}$ have been taken from Refs. [42] and [43], respectively.

Similar for the two symmetric systems, whereas $^{40}\text{Ca} + ^{48}\text{Ca}$ shows a tail toward low energies.

The coupled-channel model is able to reproduce the various experimental evidences, by using a shallow ion-ion potential, and couplings to the lowest quadrupole and octupole excitations of the colliding nuclei. Additionally, couplings to transfer channels with $Q>0$ are found to be necessary for $^{40}\text{Ca} + ^{48}\text{Ca}$.

An overall comparison with several near-by systems tell us, qualitatively, that nuclear structure is important for the fusion dynamics even far below the barrier. The available data have been discussed by considering the logarithmic slopes and the S-factors as well. Reliable extrapolations of the cross sections down to very low energies, would be of great interest for lighter systems of astrophysical interest, whose behaviour is not well known experimentally.

I am happy to express my grateful thanks to all colleagues whose ongoing and enthusiastic efforts have made possible to perform the experiments described in this paper.

7. References

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