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Sub-barrier fusion of the magic nuclei ^{40,48}Ca+^{48}Ca

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The fusion excitation functions of ^{40,48}Ca+^{48}Ca have been measured near and below the Coulomb barrier and the fusion barrier distributions have been extracted from the data. The cross sections for ^{48}Ca+^{48}Ca are well reproduced by coupled-channels (CC) calculations, including inelastic excitations to the 2^+ and 3^- states of both nuclei and using a standard potential. The cross sections of ^{40}Ca+^{48}Ca are significantly larger than previous data for the same system, especially near and above the barrier. While a much better agreement between present data and CC calculations is found in that energy range, the sub-barrier cross sections are still underpredicted.

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The fusion between two nuclei at energies close to the Coulomb barrier has been the object of extensive experimental and theoretical efforts in the past 20 years. The systematic enhancements observed with respect to one-dimensional calculations have been explained in terms of couplings to internal degrees of freedom of target and projectile, hence the sensitivity of the fusion process to nuclear structure has been recognized [1]. The possibility to extract fusion barrier distributions from accurate data [2] has brought a substantial advance in the identification of the relevant channels acting as doorways to fusion [3]. In particular, various experiments have shown the importance of static deformations [4–7] and of complex surface vibrations [8,9]. Anyway, as is often the case with intrinsically complex objects such as nuclei, the new results open new questions. The influence on sub-barrier fusion of processes such as transfer [10–13] and breakup reactions [14–16] is not yet clear; moreover, the effect of unusual structures, such as halos and skins [17], is currently being studied [18,19], although so far restricted to light nuclei.

In this context, it is important to provide a clear understanding of some fundamental test cases. One such case is the fusion between two magic nuclei. The best studied example is ^{16}O+^{208}Pb [20], whose detailed theoretical description, however, still remains elusive [21]. Other systems of great interest are the combinations of magic calcium isotopes, namely ^{40}Ca+^{40}Ca, ^{40}Ca+^{48}Ca, and ^{48}Ca+^{48}Ca. Unlike the case of ^{16}O+^{208}Pb, however, experimental data on these systems are still incomplete and, also from the theoretical point of view, the Ca+Ca systems represent a puzzle still awaiting clarification. The situation is as follows: the fusion excitation functions were measured a long time ago [22] for ^{40}Ca+^{40,44,48}Ca showing large sub-barrier fusion enhancements and conspicuous isotopic effects. The cross sections for ^{40}Ca+^{40}Ca were reproduced by detailed CC calculations [23], while the predictions for the other two systems, and in particular for ^{40}Ca+^{48}Ca, severely underestimated the data at low energies, although collective inelastic excitations and the one-nucleon transfer channel were explicitly included in the coupling scheme. A discrepancy was also found above the barrier and was judged to be particularly serious, since coupling effects on the fusion cross section are negligible at those energies. The calculations [23] overestimated the high-energy data by a factor $\approx$1.4, even with a reasonable modification of the standard ''bare'' potential, and this could hardly be attributed to systematic experimental errors; modifying the nuclear potential further makes the disagreement with sub-barrier data much larger. Therefore, the authors of Ref. [23] concluded that additional measurements for the ^{40}Ca+^{48}Ca system were necessary. Subsequent measurements of elastic scattering of ^{40}Ca+^{48}Ca near the barrier [24], moreover, gave indication that a positive Q-value channel should be included in the coupling scheme.

No data exist for the neutron-rich case ^{48}Ca+^{48}Ca and the interest in this symmetric system is twofold. First of all, if couplings to inelastic excitations can reproduce the ^{40}Ca+^{40}Ca data, the same should be true for ^{48}Ca+^{48}Ca, since ^{48}Ca also has a double closed-shell structure and both combinations offer unfavorable conditions to transfer (all Q values are large and negative). Once the inelastic couplings are fixed in ^{40}Ca and ^{48}Ca, a comparison with ^{40}Ca+^{48}Ca (where positive Q values exist) should help disentangling the possible effect of transfer couplings.

In this Rapid Communication we report on a high-precision measurement of the fusion excitation function and, consequently, of the barrier distribution of ^{48}Ca+^{48}Ca. A new set of data has also been collected for the ^{40}Ca+^{48}Ca system, with the high statistical accuracy needed to extract the fusion barrier distribution.

The experiment was performed at the XTU Tandem accelerator facility of the Laboratori Nazionali di Legnaro. The ^{40,48}Ca were produced by a sputter ion source, where CaH samples were used. The beam energy was defined with an uncertainty less than $\approx$1/800 [8] and the beam current was in the range 5–10 pnA for both ^{40}Ca and ^{48}Ca. The targets were evaporations of $^{48}CaF_2$ (50 μg/cm^2) on carbon layers 15 μg/cm^2 thick. The target isotopic enrichment was 96.78%.

In order to measure the fusion cross section well above and below the Coulomb barrier the beam energy was varied, in 800 keV steps, between 97.6 and 120.0 MeV for ^{48}Ca+^{48}Ca (V^B_{lab}=103.4 MeV), and between 88.4 and 107.6 MeV for ^{40}Ca+^{48}Ca (V^B_{lab}=97.5 MeV). For this latter system further high-energy points with a larger step were taken (up to 135.6 MeV), in order to cover the full range of the previous experiment [22]. For each system the energy was varied only downwards to minimize hysteresis effects in the energy-defining magnet.

The forward-recoiling evaporation residues (ER) were separated from the transmitted beam and beamlike particles by means of an electrostatic deflector (an improved version of the one described in Ref. [25]), whose beam rejection factor at 0° is around 10^7–10^8. The ER were further discriminated from residual beamlike particles by means of an energy–time of flight (E-TOF) telescope based on a microchannel plate detector and on a 300 mm^2 silicon surface-barrier detector; the geometrical solid angle of the telescope was 2.2×10^{-2} msr. The identification of ER in the E-TOF plane is very clear (see, e.g., Ref. [9]). Four silicon monitor detectors with a solid angle 4.13×10^{-2} msr were placed symmetrically at $\theta_{lab}=16°$ to the beam direction to detect the Rutherford scattering from the target. This allowed us to establish the beam direction for each run with an accuracy better than 0.1°. Small deviations from 0° due to different beam focusing were taken into account in the data reduction. The transmission of the electrostatic deflector was determined to be $0.60(0.55)\pm0.06$ for ^{48}Ca+^{48}Ca (^{40}Ca+^{48}Ca), by Monte Carlo simulations (see Ref. [11]).

ER angular distributions were measured in steps of 1° at $E_{lab}=116$ and 104 MeV in the range $-5°$ to $+3°$ for ^{48}Ca+^{48}Ca and at $E_{lab}=107.6$ (98.8) MeV in the range $-7°$ to $+6°$ ($-5°$ to $+4°$) for ^{40}Ca+^{48}Ca. The angular distributions are symmetrical around 0° and they drop more slowly for ^{40}Ca+^{48}Ca (FWHM≈5°) than for ^{48}Ca+^{48}Ca (FWHM≈3°). As in our previous experiments (see Ref. [9] and references therein), no significant energy dependence of the width and shape of the angular distributions was found, therefore the measurements performed at the two energies for each system were combined. The angular distributions were fitted by a Gaussian and integrated, thus obtaining the ratio of the yield at 0° to the total yield of ER. For each energy, the number of ER events was normalized to the elastic scattering yield in the monitor detectors. The normalization was performed according to the Rutherford cross section for ^{40}Ca+^{48}Ca, and to the oscillating Mott function for the symmetric ^{48}Ca+^{48}Ca system. By taking into account the solid angles, the transmission factor and the 0°-to-total ratio, the ER yields were transformed into total fusion cross sections (fusion-fission is negligible).

The measured fusion excitation functions are shown in Fig. 1 as a function of the center-of-mass energy divided by the Coulomb barrier and in Fig. 2 (points) in an absolute energy scale. The statistical uncertainties are of the order of 1% for the higher and intermediate energies and increase to ≈10% for the lowest energies, but these statistical errors are essentially the only ones affecting relative cross sections within one system. Systematic errors, taking into account the transmission factor, the geometrical solid angle uncertainties, and the angular distribution integration, sum up to ±15%. Larger oscillations can be seen for ^{48}Ca+^{48}Ca above $E_{c.m.}\geqslant57$ MeV for some points, and may be due to imperfect beam focusing.

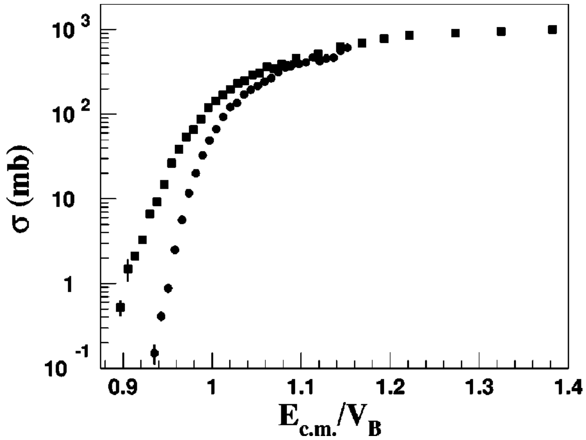

FIG. 1. Fusion cross section for ^{48}Ca+^{48}Ca (circles) and ^{40}Ca+^{48}Ca (squares) measured in this work, as a function of the reduced center-of-mass energy. The error bars represent purely statistical uncertainties.

The deformation parameters of the relevant inelastic excitations of ^{40}Ca and ^{48}Ca are reported in Table I. The 2^+ and 3^- states for both nuclei lie at high energies, and while the 2^+ states are of comparable strength, a much stronger octupole vibration is present in ^{40}Ca, causing a renormalization of the bare potential. The net expected effect, qualitatively, is a shift of the Coulomb barrier of a few MeV and, as a consequence, larger low-energy fusion cross sections; this is what our data show (see Fig. 1), together with a difference

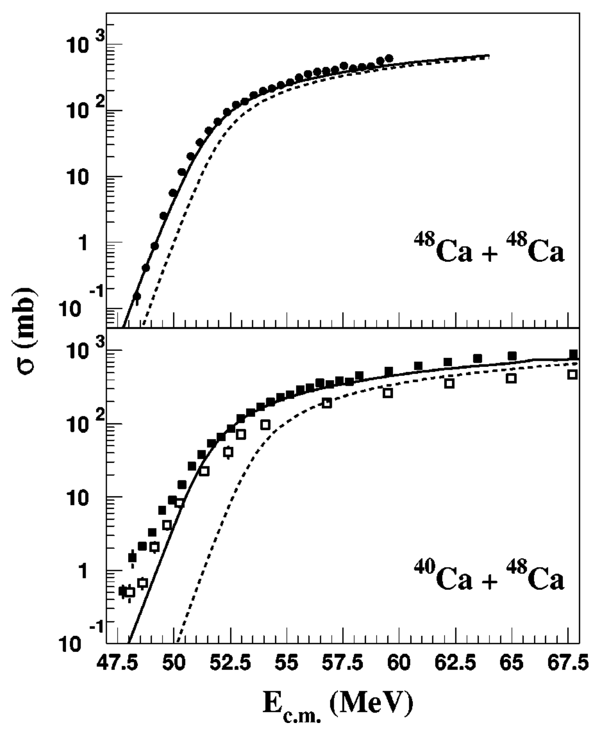

FIG. 2. Fusion excitation function (points) compared with CC calculation (full lines) for ^{48}Ca+^{48}Ca (top panel) and ^{40}Ca+^{48}Ca (bottom panel). The no-coupling limit is also reported (dashed lines). The data from Aljuwair *et al.* [22] (open squares) are shown for comparison.

TABLE I. Excitation energies E_x, spin and parities λ^π, and deformation parameters β_C and β_n of the relevant states of ^{48}Ca and ^{40}Ca.

Nucleus	E_x (MeV)	λ^π	β_C	β_n
^{48}Ca	3.832	2^+	0.122	0.184
	4.507	3^-	0.134	0.170
^{40}Ca	3.904	2^+	0.101	0.091
	3.737	3^-	0.433	0.293

in slope between the two systems at sub-barrier energies, which, however, should be attributed to effects other than inelastic excitations.

The data have been analyzed within the framework of the CC formalism using the code CCFULL [26]. This program takes into account the effects of vibrational couplings to all orders, and in the harmonic limit. The no-Coriolis (or isocentrifugal) approximation, consisting of replacing the angular momentum of the relative motion in each channel by the total angular momentum, is employed to reduce the number of CC equations and the incoming-wave boundary condition is used inside the Coulomb barrier.

The present calculations include the 2^+ and 3^- states of ^{48}Ca and ^{40}Ca; considering, in addition, mutual excitation does not produce any significant change of the results for both excitation functions and barrier distributions. The Coulomb deformation parameters β_C have been extracted from tabulated values [27,28]. The nuclear deformation parameters β_n have been taken from [29], i.e., from the analysis of inelastic scattering of ^{16}O+ ^{40,48}Ca. As a matter of fact, we have chosen to use the same parameters as in Ref. [23], with $\beta_n \neq \beta_C$, for comparison. Taking $\beta_n = \beta_C$ has anyway little effect on the calculations. All the spectroscopic inputs to the calculations are listed in Table I. The standard Akyüz-Winther [30] potential was used and the potential parameters, together with the deduced barrier parameters, are reported in Table II.

The results of the CCFULL calculations are shown by full lines in Fig. 2 for ^{48}Ca+^{48}Ca (top panel) and ^{40}Ca+^{48}Ca (bottom panel). The no-coupling limits are also reported (dashed lines). The previous data of Aljuwair *et al.* [22] for ^{40}Ca+^{48}Ca are shown for comparison. The present data for ^{40}Ca+^{48}Ca are a factor ≈ 2 larger than the previous ones at high energy, pointing in the direction suggested by previous theoretical analyses [23]. As can be seen in Fig. 2, the excitation function for ^{48}Ca+^{48}Ca is well reproduced by CC calculations over the whole energy range. No attempt was done to fit the data. By the way, there is no evidence of

TABLE II. The ion-ion potential parameters used in the calculations, together with the deduced barrier parameters.

System	V_0 (MeV)	r_0 (fm)	a (fm)	V_B (MeV)	R_B (fm)	$\hbar\omega$ (MeV)
^{48}Ca+^{48}Ca	64.104	1.175	0.662	51.7	10.38	3.27
^{40}Ca+^{48}Ca	64.925	1.174	0.657	53.2	10.08	3.52

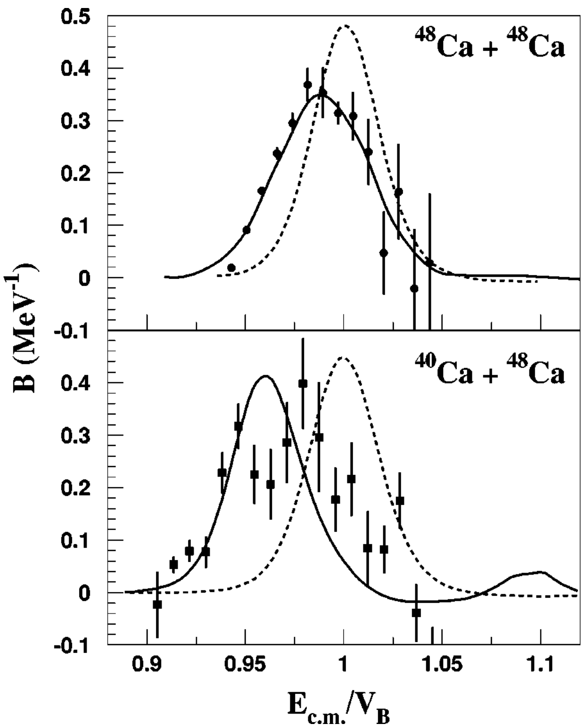

FIG. 3. Fusion barrier distribution (points) compared with CC calculations (full lines) for ^{48}Ca+^{48}Ca (top panel) and ^{40}Ca+^{48}Ca (bottom panel). The dashed lines show the results of no-coupling calculations. The points for $E_{\mathrm{c.m.}}/V_B \geqslant 1.05$ have very large error bars and are not reported.

enhancements due to the thin neutron skin [31,32] nor to the coupling to the low-lying resonant state (possibly a soft dipole mode) of ^{48}Ca [33], contrary to what has been recently observed for the fusion of the light weakly-bound projectile ^{6}He with ^{209}Bi [18] and ^{238}U [19].

For the system ^{40}Ca+^{48}Ca, the agreement is good at above-barrier energies, but the low-energy data are underestimated by our CC calculation. The discrepancy was over 2 orders of magnitude at low energies between previous data and calculations [23]; it is now reduced and we are able to reproduce the high-energy data with a standard potential, without any adjustment. The residual sub-barrier enhancement, and the difference in slope between the two systems, cannot be due to inelastic excitations and may be indication of transfer couplings, as previously suggested in Ref. [23]. Indeed, positive Q values exist for neutron pickup channels (e.g., $Q_{+2n} = 2.62$ MeV, $Q_{+4n} = 3.88$ MeV) and even for proton stripping channels (e.g., $Q_{-2p} = 7.08$ MeV, $Q_{-4p} = 7.02$ MeV).

The barrier distributions were extracted from the fusion excitation functions as the second energy derivatives of $E\sigma_f$ [2], where the three-point difference formula [4] was applied with $\Delta E_{lab} = 1.6$ MeV, since using a smaller energy interval in that formula leads to very large error bars. (For ^{48}Ca+^{48}Ca, the points at $E_{\mathrm{c.m.}}/V_B \geqslant 1.0$ were derived with $\Delta E_{lab} = 2.4$ MeV.) The corresponding distributions are shown in Fig. 3 (points). The plotted quantity B is $d^2(E\sigma_f)/dE^2$ normalized to πR_B^2, where R_B is the barrier radius. The corresponding CC calculations are shown by full lines; the no-coupling results are also reported (dashed lines). The experimental fusion barrier distribution for ^{48}Ca+^{48}Ca has only one peak, due to the very rigid nature of target and projectile, and is well reproduced by CC calculations. On the other hand, the experimental barrier distribution for ^{40}Ca+^{48}Ca has two clear peaks at $E_{\mathrm{c.m.}}/V_B \simeq 0.95, 0.98$ and, possibly, a much weaker structure at low energies ($E_{\mathrm{c.m.}}/V_B \simeq 0.92$). These features of the barrier distribution are responsible for the enhancement observed in the sub-barrier fusion cross section, and are not reproduced by CC calculations including couplings to inelastic excitations only, even considering mutual excitations. Those features may be further evidence of transfer couplings (see, e.g., [10]), supporting the conclusions of Ref. [23], based on the observation of the fusion enhancement, and those of Ref. [24], based on elastic scattering results. The dominant effect in the calculated barrier distribution is a ≈ 2 MeV shift of the main peak, due to the strong octupole vibration of ^{40}Ca, with respect to the no-coupling limit (the shift is much smaller for ^{48}Ca+^{48}Ca).

In conclusion, our measurements represent a significant step towards the comprehension of fusion dynamics in Ca+Ca systems. Fusion excitation function and barrier distribution of ^{48}Ca+^{48}Ca have been measured near and below the Coulomb barrier for the first time. A new set of data with good statistical accuracy has also been collected for the long debated ^{40}Ca+^{48}Ca system, showing a large discrepancy with previous data at high energies. A very good agreement between data and CC calculations has been obtained for the symmetric ^{48}Ca+^{48}Ca case over the whole energy range, confirming the reliability of the theoretical model. The same holds for ^{40}Ca+^{48}Ca, where standard CC calculations are able to reproduce the present above and near-barrier cross sections. However, a significant discrepancy is still present at low energies for this system. This enhancement, together with the peculiar features of the barrier distribution, may be an indication of transfer couplings. Further measurements of elastic scattering and of single- and multinucleon transfer in ^{40}Ca+^{48}Ca, as well as more complete and detailed CC calculations, possibly including transfer couplings, would be very useful to put such indications on a more solid ground.

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