Isotopic effects in the fusion of ^{40}Ca with ^{40,44,48}Ca

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Excitation functions for fusion of ^{40}Ca+^{40,44,48}Ca have been measured over a range of energies from below to well above the classical fusion barrier. Strong isotopic effects are observed in both the sub- and above-barrier cross sections, which are qualitatively consistent with suggestions of the importance of transfer reactions in the fusion process.

Cross sections for the fusion of heavy nuclei at energies below the classical fusion barrier have been found to exhibit two features which are the subject of much current interest.[1–7] First, the magnitudes of these sub-barrier fusion cross sections are severely underpredicted by simple one-dimensional barrier penetration models which give a reasonable description of the above-barrier fusion data. Second, large differences are observed in both the magnitudes and energy dependence of sub-barrier fusion cross sections for different isotopes of the same element,[1–6] a feature which is again not accounted for by currently available models.

A variety of models[1–14] have been proposed to explain the sub-barrier fusion data including modifications of the real potential due to static deformation[13] and zero-point collective motion,[10] as well as dynamically induced deformation.[11] It has also been proposed that couplings[12,14] to specific collective states and/or particle exchange may play a role in the observed enhancements and isotopic dependence of sub-barrier fusion cross sections. As yet, however, no clear understanding of the relative importance of all these mechanisms has emerged. It therefore seems that only by detailed study of many nuclear systems with well-known and understood properties will a quantitative understanding of the fusion process emerge.

In this paper, we report on the results of measurements of the fusion of ^{40}Ca + ^{40,44,48}Ca. These measurements are being complemented by measurements[15] of the elastic, inelastic, and transfer reaction cross sections. The totality of these data will thus provide a set of cross sections for all strong reaction channels for a range of nuclei with well-known and quite different properties.

The fusion measurements were performed at the Brookhaven National Laboratory Tandem Van de Graaff Facility. Targets of enriched ^{40}Ca (99.97%), ^{44}Ca (98.5%), and ^{48}Ca (89.9%) with areal densities of 100 μg/cm^2 on carbon backings were bombarded with a ^{40}Ca beam of energies between 89 and 135 MeV. The energy loss of the beam through the targets was taken into account in the data shown in Figs. 1—3.

Excitation functions of evaporation residue cross sections were measured using the MIT-BNL velocity selector. The scattering chamber included a carbon slit arrangement which limited the beam spot to approximately 1 mm by 2 mm, a 20 μg/cm^2 carbon reset foil which was placed approximately 10 cm after the target to ensure charge equilibration, and two symmetrically placed monitor detectors for cross section normalization. Particles emerging from the velocity selector were detected in a ΔE-E telescope. The electronics included a pile-up reject circuit with 20 ns to 3 μs rejection capability which ensured that piled-up beam-tail events were not misidentified as evaporation residues.

The efficiency of the velocity selector is a function of both the charge and velocity of the evaporation residues. In order to obtain total fusion cross sections it is, there-

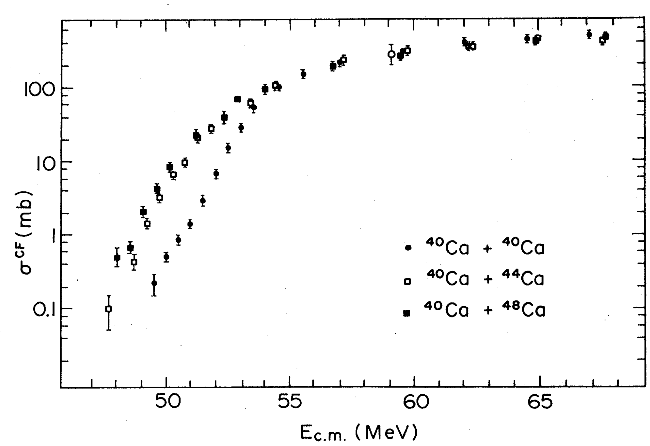

FIG. 1. Excitation functions of the fusion cross sections for the ^{40}Ca + ^{40,44,48}Ca systems measured with the MIT-BNL velocity selector. The open circle at $E_{\rm c.m.}=59$ MeV is the result of a time-of-flight measurement (see the text).

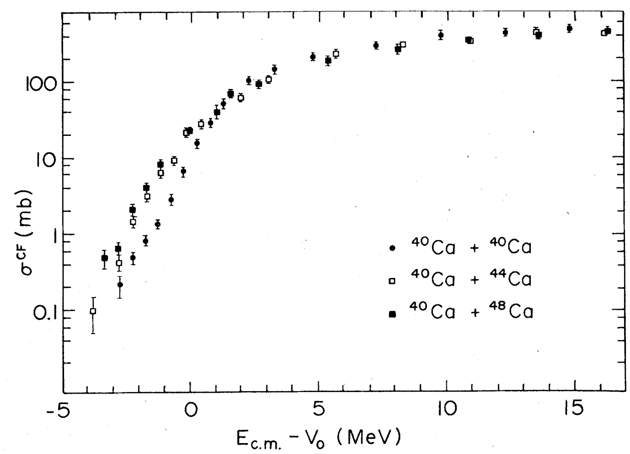

FIG. 2. Fusion excitation functions of the $^{40}Ca + {}^{40,44,48}Ca$ systems plotted as a function of $(E_{c.m.} - V_0)$.

fore, necessary to measure velocity and charge distributions as well as angular distributions. The charge state (q) distribution was measured for $^{40}Ca + {}^{40}Ca$ at $E_{lab} = 120$ MeV. The measured mean charge state ($q = +17.7e$) was found to be approximately one atomic charge unit smaller than that predicted by published systematics.[16] The mean charge state for other energies (and for the other Ca systems) were obtained by normalizing the measured mean at 120 MeV and then using the velocity dependence of q as deduced by Betz.[16] The close agreement between the measured mean and the predicted mean suggest that this is a reliable procedure. Angular distributions were measured between $\theta_{lab} = 0°-7°$ in 1 deg steps. Angular distributions were measured at $E_{lab} = 120$ and 108 MeV for $^{40}Ca + {}^{40}Ca$; $E_{lab} = 130$, 115, and 103 MeV for $^{40}Ca + {}^{44}Ca$; and at $E_{lab} = 130$, 110, and 98 MeV for $^{40}Ca + {}^{48}Ca$. The cross section, $d\sigma/d\theta$, peaked at approximately $\theta_{lab} = 3°$ for all energies, and dropped by an order of magnitude by $\theta_{lab} = 7°$. Velocity distributions were measured at $\theta_{lab} = 0°$ for every energy at which an angular distribution was measured. Additionally, velocity distributions were measured at $\theta_{lab} = 3°$ and 6° for some energies and were found to be in good agreement with the 0° distributions.

Total fusion cross sections were obtained at energies for which angular and velocity distributions were measured by integrating these distributions and correcting them for the charge state efficiency of the velocity selector. The charge state efficiency was calculated using a ray-tracing code, the parameters of which have been previously experimentally extracted.[1] The total systematic error in this procedure is expected to be less than 20%. The total fusion cross sections at other energies were obtained by measuring the 0° evaporation residue cross section using field settings for the velocity selector set for the mean charge state and velocity of the residue and then interpolating or extrapolating the cross section normalizations discussed previously. The uncertainties in the interpolated cross sections (between $E_{c.m.} = 54-60$ MeV for $^{40}Ca + {}^{40}Ca$, $E_{c.m.} = 53.9-68.1$ MeV for $^{40}Ca + {}^{44}Ca$, and

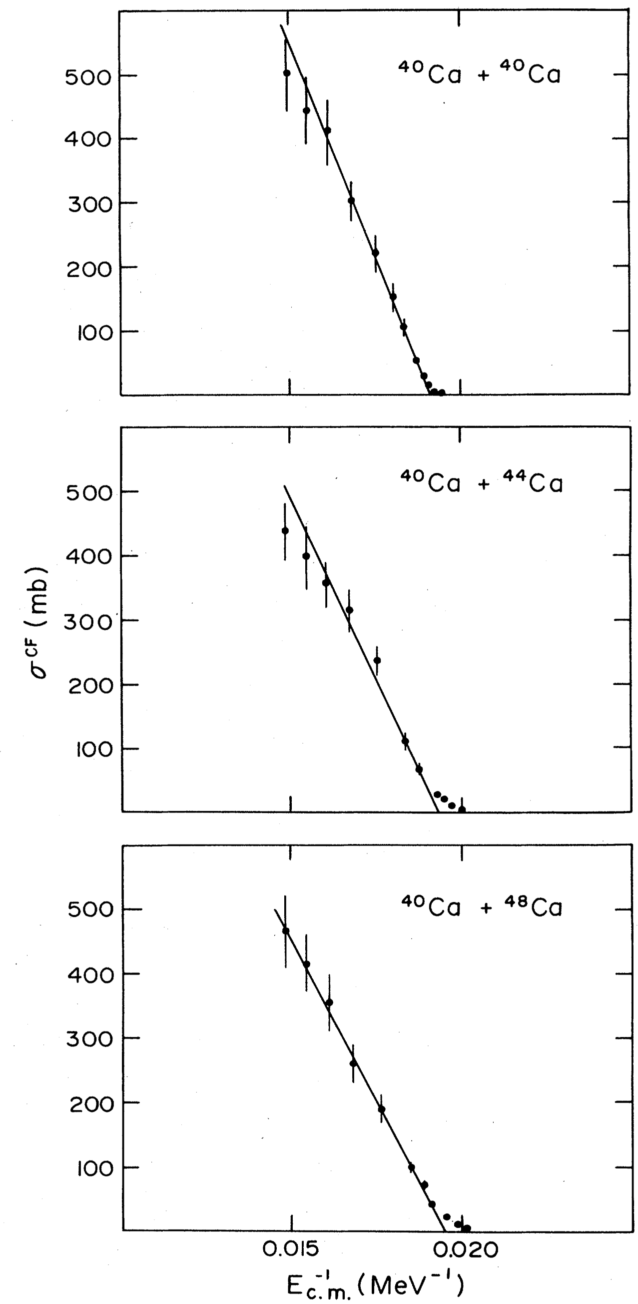

FIG. 3. Cross sections for fusion of $^{40}Ca + {}^{40,44,48}Ca$ plotted vs $E^{-1}_{c.m.}$. The solid line is a fit to the above-barrier cross sections with the parametrized expression $\sigma^{CF} = \pi R_0^2(1 - V_0/E_{c.m.})$. In some cases the highest energy points were excluded from the fit.

$E_{c.m.} = 53.5-70.9$ MeV for $^{40}Ca + {}^{48}Ca$) are less than 10%. The same relative error of 10% has been assumed for the extrapolated cross sections. All error bars include a 10% relative error added in quadrature with the statistical error.

An independent measurement of the $^{40}Ca + {}^{40}Ca$ fusion cross section at $E_{c.m.} = 59$ MeV was made at the Argonne National Laboratory superconducting linac facility using a ΔE-E time-of-flight technique. This value agrees with that obtained from the velocity selector to within 10%.

Previous measurements of the ^{40}Ca + ^{40}Ca fusion cross section have been made by Doubre *et al.*[17] and Tomasi *et al.*[18] using ΔE-E ionization chambers, and by Barreto *et al.*[19] using gamma-ray techniques. The agreement between these three sets of data and the present data is rather poor. The present results lie between those of Doubre *et al.*, which are higher, and those of Tomasi *et al.* and Barreto *et al.*, both of which are lower than the present results. The origin of these discrepancies is not known, although all four sets of data are in reasonable agreement near $E_{\mathrm{c.m.}} = 70$ MeV. The disagreements are most pronounced at the lowest energies where the measurements are most difficult.

The measured fusion cross sections shown in Fig. 1 span almost four orders of magnitude, from approximately 500 mb at the highest measured energies down to 0.1 mb at energies below the barrier. The sub-barrier cross sections show conspicuous differences between the ^{40}Ca and ^{44,48}Ca targets. The cross sections for ^{40}Ca + ^{40}Ca fall much faster with decreasing energy and become approximately an order of magnitude smaller than those for ^{40}Ca + ^{44}Ca and ^{40}Ca + ^{48}Ca. This trend is similar to that previously observed[1] in the sub-barrier fusion of Ni + Ni.

The fusion excitation functions are shown in Fig. 2 as a function of $(E_{\mathrm{c.m.}} - V_0)$. This demonstrates that even after corrections for barrier heights there are distinct differences in the sub- and near-barrier fusion excitation functions. In particular, the ^{40}Ca + ^{44,48}Ca systems have larger sub-barrier fusion cross sections than ^{40}Ca + ^{40}Ca. The shape of the ^{40}Ca + ^{40}Ca fusion excitation function is steeper than for the other systems and is closer to what is expected in simple one-dimensional barrier-penetration models.

The $l = 0$ barrier heights (V_0) and radii (R_0) were obtained from the above-barrier cross sections using fits with both the Glas and Mosel[20] parametrization and calculations of penetration through a one-dimensional parabolic barrier matched at large distances to a Coulomb tail. Both procedures gave essentially identical values for V_0 and R_0. These are listed in Table I. The Glas and Mosel fits are shown with the data plotted vs $E_{\mathrm{c.m.}}^{-1}$ in Fig. 3.

In addition to the sub-barrier effects, there are also significant, but less obvious, isotopic effects in the above-barrier cross sections. The values obtained for V_0 are in good agreement with those in published systematics[21] and are close to, but lower than, those predicted using potentials derived from the liquid drop model such as that due to Krappe, Nix, and Sierk (KNS) (Ref. 22) or Akyüz and Winther (AW) (Ref. 23). The barrier radii, however, show a dependence on target which is quite different from that expected. The values of R_0 extracted from the data show a significant decrease in going from ^{40}Ca to ^{44}Ca to ^{48}Ca, contrary to the slight increase expected on the basis of an $(A_1^{1/3} + A_2^{1/3})$ dependence and systematics of fusion radii,[21] or the constant value expected from radii of Ca isotopes extracted from hadron scattering.[24] The value of R_0 for the ^{40}Ca + ^{40}Ca system is in good agreement with the systematics of Ref. 21.

The decrease in R_0 with increasing mass reflects the experimentally observed smaller fusion cross sections for ^{44}Ca and ^{48}Ca as compared to ^{40}Ca. If we assume that the total reaction cross section remains constant, or increases only slightly, as suggested by the known matter radii, this suggests a considerably increased cross section for nonfusion reactions such as inelastic scattering or particle transfer for the ^{44}Ca and ^{48}Ca targets. This expectation is consistent with the known level structure of the Ca isotopes and Q values for particle transfer. It is expected that particle transfer channels with positive Q values will be much stronger than those with negative Q values (the change in the Coulomb barriers for small numbers of transferred particles being quite small in the present case). The Q values for one- and two-nucleon pickup and stripping reactions are given in Table II. The closed shell $T = 0$ nature of ^{40}Ca ensures that all one- and two-particle transfer Q values are large and negative ($Q_0 = -7.25$ and -7.27 MeV for 1p and 1n transfer, respectively). For ^{40}Ca + ^{44}Ca, the one-proton stripping reaction ^{44}Ca(^{40}Ca,^{39}K)^{45}Sc has $Q_0 = -1.44$ MeV, and for ^{48}Ca the corresponding reaction ^{48}Ca(^{40}Ca,^{39}K)^{49}Sc has $Q_0 = +1.29$ MeV. For ^{40}Ca + ^{40}Ca, the two-particle transfer Q values are all very negative, but are positive for

^{44}Ca(^{40}Ca,^{42}Ca)^{42}Ca ,

^{44}Ca(^{40}Ca,^{38}Ar)^{46}Ti ,

^{48}Ca(^{40}Ca,^{42}Ca)^{46}Ca ,

and

^{48}Ca(^{40}Ca,^{38}Ar)^{50}Ti .

For the inelastic channels, ^{40}Ca and ^{48}Ca have only moderately and weakly collective states, which lie at relatively high excitation energies, whereas ^{44}Ca has a low lying (1.44 MeV) collective 2^+ state, which would therefore be expected to be strongly excited.

These same systematics of particle transfer Q values

TABLE I. Values of V_0 and R_0 extracted from the above-barrier data and values from systematics (Ref. 21) and theoretical potentials (Refs. 22 and 23).

		R_0 (fm)		V_0 (MeV)		
System	$A_1^{1/3} + A_2^{1/3}$	Expt.	Ref. 21	Expt.	KNS	AW
^{40}Ca + ^{40}Ca	6.84	8.8±0.5	9.2	52.3±0.5	55.9	54.9
^{40}Ca + ^{44}Ca	6.95	8.5±0.5	9.3	51.7±1.2	55.0	54.0
^{40}Ca + ^{48}Ca	7.05	7.8±0.3	9.4	51.3±1.0	54.3	53.2

TABLE II. The ground state Q values (first line) and the change in the Coulomb barrier (second line) between the entrance and exit channels (in MeV) for the indicated transfer reactions. The Coulomb barriers were computed using the expression $E_C = Z_1 Z_2 e^2/R_0$, with the values of R_0 taken from Table I.

	Pickup		Stripping		Pickup		Stripping	
System	1p	1n	1p	1n	2p	2n	2p	2n
$^{40}Ca + ^{40}Ca$	−7.25	−7.27	−7.25	−7.27	−9.86	−9.13	−9.86	−9.13
	+0.16	0.00	+0.16	0.00	+0.66	0.00	+0.66	0.00
$^{40}Ca + ^{44}Ca$	−11.09	−2.77	−1.44	−8.22	−16.77	+0.77	+2.53	−11.15
	+0.17	0.00	+0.17	0.00	+0.68	0.00	+0.68	0.00
$^{40}Ca + ^{48}Ca$	−14.72	−1.59	+1.29	−10.49	−24.21	+2.61	+7.08	−17.47
	+0.19	0.00	+0.19	0.00	+0.74	0.00	+0.74	0.00

and inelastic excitation have been suggested[12,14] as being responsible for the observed differences in sub-barrier fusion cross sections. The effects seen in the present sub-barrier data are similar to those observed in $^{58}Ni + ^{58}Ni$ and $^{58}Ni + ^{64}Ni$ fusion. Broglia *et al.*[12] and Dasso *et al.*[14] have linked this behavior to fusion through the positive Q-value transfer channels. They argue that if transfer takes place into a channel where $Q + \Delta E_C$ is positive [ΔE_C being the difference in the Coulomb barrier between the transfer and incident channel (see Table II)], then the larger effective energy in the new channel will increase the fusion probability. A comparison between the $^{40}Ca + ^{40}Ca$ and $^{40}Ca + ^{48}Ca$ systems is particularly interesting in this connection since, for both systems, the inelastic channels are similar (i.e., no low-lying collective states) and would not be expected to increase the fusion probability. The positive one- and two-nucleon transfer Q values for $^{40}Ca + ^{48}Ca$ as compared to the very negative transfer Q values for $^{40}Ca + ^{40}Ca$ should, according to the above argument, increase the fusion probability for $^{40}Ca + ^{48}Ca$ relative to $^{40}Ca + ^{40}Ca$. This is consistent with the measured fusion cross sections (see Fig. 1). Of course, the details of the present fusion data, such as the near identity of the $^{40}Ca + ^{44}Ca$ and $^{40}Ca + ^{48}Ca$ fusion cross sections, cannot be inferred from such qualitative arguments. It seems, nevertheless, that there may be an intimate connection between particle transfer and the fusion cross section.

From an experimental point of view, measurements of the relevant transfer and inelastic channels for $^{40}Ca + ^{40,44,48}Ca$ are of obvious importance since these quantities enter directly into the coupled channels picture suggested in Refs. 12 and 14. These measurements are in progress.[15]

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