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Author
Morrissey, D.J.

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D. J. Morrissey, W. Loveland, R. J. Otto, and
G. T. Seaborg

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LOWERED FUSION CROSS SECTION IN THE QUADRUPLY MAGIC HEAVY ION SYSTEM, ^{48}Ca + ^{208}Pb*

D. J. Morrissey, W. Loveland,[†] R. J. Otto
and G. T. Seaborg

Lawrence Berkeley Laboratory
and Department of Chemistry
University of California
Berkeley, California 94720

ABSTRACT

The results of radioanalytical mass yield distribution studies of the reaction of ^{48}Ca with thick ^{208}Pb targets at the effective laboratory energies of 255 and 300 MeV are reported. Complete fusion cross sections are found to be significantly lower than those found for ^{40}Ar induced reactions with non-magic targets apparently showing the effect of the projectile and target nuclear structure on such cross sections.

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In an attempt to understand better the reactions of a near unique quadruply-magic projectile-target system we have studied the reaction of the doubly-magic ^{48}Ca projectile with the relatively non-fissionable doubly magic ^{208}Pb target. In this paper, we report complete fusion cross sections for this doubly-magic projectile-target system that are unexpectedly small when compared to similar cross sections for non-magic systems.

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[†] Permanent address: Department of Chemistry, Oregon State University, Corvallis, Oregon 97331.

Isotopically pure ^{208}Pb targets of thickness 42-45 mg/cm^2 were irradiated with beams of ^{48}Ca ions of incident energy 300 and 410 MeV from the SuperHILAC of the Lawrence Berkeley Laboratory. The lower energy bombardment lasted 60 minutes with an average intensity of ~9.3 x 10^{13} particles/minute while the higher energy bombardment lasted for 108 minutes with an average intensity of ~4.7 x 10^{13} particles/minute. Absolute cross sections were measured only in the higher energy bombardment due to difficulties in determining the number of ^{48}Ca ions passing through the target in the lower energy irradiation. Following the bombardments the induced radioactivities in the target were detected with a Ge(Li) γ-ray spectrometer. The decay of the observed activities was followed for a period of approximately two months. Specific radionuclides produced were identified on the basis of γ-ray energy, half-life and relative abundance of associated γ-rays.

In this manner 94 and 109 radionuclides were identified in the low and high energy reactions, respectively. Using the procedures previously developed to analyze heavy ion reaction mass distributions,[1] we calculated independent yields for each observed radionuclide and consistent Gaussian charge dispersions were fitted to the independent yields. The Gaussian charge dispersions were integrated to give the isobaric yield for each mass number where a radionuclide was observed. The measured partial cumulative and independent yields represented ~15% to ~50% of the final isobaric mass yields that are shown in Figures 1(a) and 1(b).

The relative contributions to the measured mass distributions from complete fusion-fission and the fission of deep inelastic lead-like species were evaluated by non-linear least squares fitting our best estimates for the shapes of the mass distributions from these processes to the measured data. The shape of the mass distribution from the fission of Pb-like products, component B, was estimated by using mass distributions from charged particle induced fission.[2] The shape of the mass distribution from the fission of the No compound nucleus, component A, in the lower energy reaction was constructed from the measured ^{252}No spontaneous fission mass distribution,[3] and the mass distributions for the compound nucleus fission from the reaction of light ions (^{4}He, ^{12}C, ^{16}O) with U and Pu targets.[4] The shape of component A from the higher energy complete fusion-fission reaction is thought to be a symmetric Gaussian shape with a FWHM ~70 amu.[5] Recoil loss corrections, calculated as a function of fission product mass number, were made for the complete fusion-fission products and the deep inelastic induced fission of lead-like products. These calculated recoil loss corrections ranged from ~20% to ~2% for A=40 to 160, respectively.

Component C and component D in Figures 1(a) and 1(b) represent the projectile-like and target-like deep inelastic components respectively. The dotted curve shown centered around mass 206 in Figure 1(b) is the reflection of component C before fission and neutron evaporation. The shape of component D in Figure 1(b) is a result of the balance between the excitation energy, generally increasing with large mass exchange in the lead-like deep inelastic fragments, and their loss by fission which generally increases with Z. The shaded curve represents the sum of the components A, B, C and D and the uncertainty in the overall fits under a variety of assumptions. (The high yields above the curve representing the sum of components A, B, C and D in the region A~170, Figure 1(a), and ~140, Figure 1(b), are the result of large corrections, with their consequent uncertainties, to these measured yields which are far from the most probable charge for their isobars.) Finally, the quasi-elastic transfer mass distribution is defined by component E. Component F represents a reflection of this distribution. The product nuclides that make up component F are unsuitable for radioanalytical detection.

Figure 1(b) shows the results of the best least squares component analysis of the mass distribution for the high energy reaction. Component B(÷2) = 200±40 mb plus the heavy deep inelastic peak, component D = 420±20 mb, is approximately equal to component C = 570±50 mb, as expected. However, our main interest is in the value of the complete fusion cross section, σ_{CF}, component A(÷2) = 600±70 mb. Component E, the quasi-elastic transfer products, is equal to ~600 mb. Thus the measured total reaction cross section σ_R = 1770±90 mb. The mean geometrical reaction cross section, $\bar{\sigma}_R$, can be calculated from the equation:

$$\bar{\sigma}_R = \pi R^2 \quad \frac{\int_B^E (1-B/E)dE}{(E-B)} \quad = 1750 \text{ mb},$$

where the interaction barrier, B, is 212 MeV, the incident projectile energy (lab), E, is 410 MeV and the interaction radius, R, is 13.7 fm. This analysis gives σ_{CF} = 34±7% of σ_R and an effective projectile energy in the thick target of 300 MeV.

Figure 1(a) shows the results of a least squares component analysis of the mass distribution from the low energy reaction. We can calculate the absolute magnitude of each component cross section by knowing what fraction of the measured total reaction cross section it represents. The cross sections for each of the components shown in Figure 1(a) (with recoil loss corrections) are: component A(÷2) = 235±45, component B(÷2) = 55±15, component C = 200±15, component D = 175±40, component E = 555±80. These values are based on a calculated $\bar{\sigma}_R$ = 990 mb, and the effective bombarding energy is 255 MeV. Thus σ_{CF} represents only 24±10% of σ_R at this energy.

In ^{40}Ar induced reactions$^{6-8}$, in which the complete fusion fission cross section was determined, σ_{CF} was found to be ~50% of σ_R. Thus, our measured complete fusion cross sections for ^{48}Ca + ^{208}Pb are unexpectedly low. In order to make meaningful comparisons, we have plotted (in Figure 2) the values of σ_{CF} from this work and measurements of σ_{CF} for the interaction of ^{40}Ar projectiles with medium and high mass targets[6-8] versus the parameter B/E, the laboratory interaction barrier divided by the effective laboratory energy of the projectile. As shown in Figure 2 a plot of σ_{CF} versus B/E for a common projectile with several targets defines a common curve. On this basis we conclude that the value of σ_{CF} for the ^{48}Ca + ^{208}Pb system is significantly lower than that found for ^{40}Ar induced reactions, with non-magic targets, at comparable energies. Glas and Mosel[9] have predicted the general behavior of the complete fusion cross sections that is seen in Figure 2 and have suggested that a lower fusion cross section might be observed for doubly-magic systems due to a smaller critical radius.

Additional evidence for this comes from mass distribution studies of the reaction of ^{40}Ar with non-magic ^{197}Au[10] and magic ^{209}Bi[11] targets. These thick target experiments were done at effective B/E values of 0.71 and 0.74 respectively and are therefore directly comparable with the high energy ^{48}Ca results. The cross section for the quasi-elastic transfer reaction represents 30% - 35% of the total reaction cross section for all three reactions (^{40}Ar + Au, ^{40}Ar + Bi and ^{48}Ca + Pb). The deep inelastic cross sections, however, are ~20% (for ^{40}Ar + Au), ~30% (for ^{40}Ar + Bi) and ~30% (for ^{48}Ca + Pb) while the complete fusion cross sections show the opposite trend, ~50% (^{40}Ar + Au), ~40% (^{40}Ar + Bi) and ~34% (^{48}Ca + Pb). These trends support the conclusion that the closed shell nature of the target and projectile contribute effectively to the reduction of σ_{CF}.

The lowered fusion cross sections might indicate an enhanced barrier to complete fusion for this system; however, the results of Flerov et al.[12] and Nitschke et al.[13] show that no such enhanced barrier exists for the evaporation residue products such as ^{254}No. This finding of a depressed fusion cross section for the ^{48}Ca + ^{208}Pb reaction should serve as a challenge for theoretical studies of these reactions to explain the apparent effect of projectile-target nuclear structure on the complete fusion cross section.

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FIGURE CAPTIONS

Fig. 1. (a) Product mass distributions from the bombardment of the ^{208}Pb with ~255 MeV ^{48}Ca. (b) Same as (a) except ^{48}Ca energy ~300 MeV. Parenthetical points indicate members of an isomeric pair where the isobaric yield can be split between both members. For an explanation of curves see text.

Fig. 2. Representation of the complete fusion cross section, σ_{CF}, for ^{40}Ar and ^{48}Ca induced reactions versus the parameter B/E.

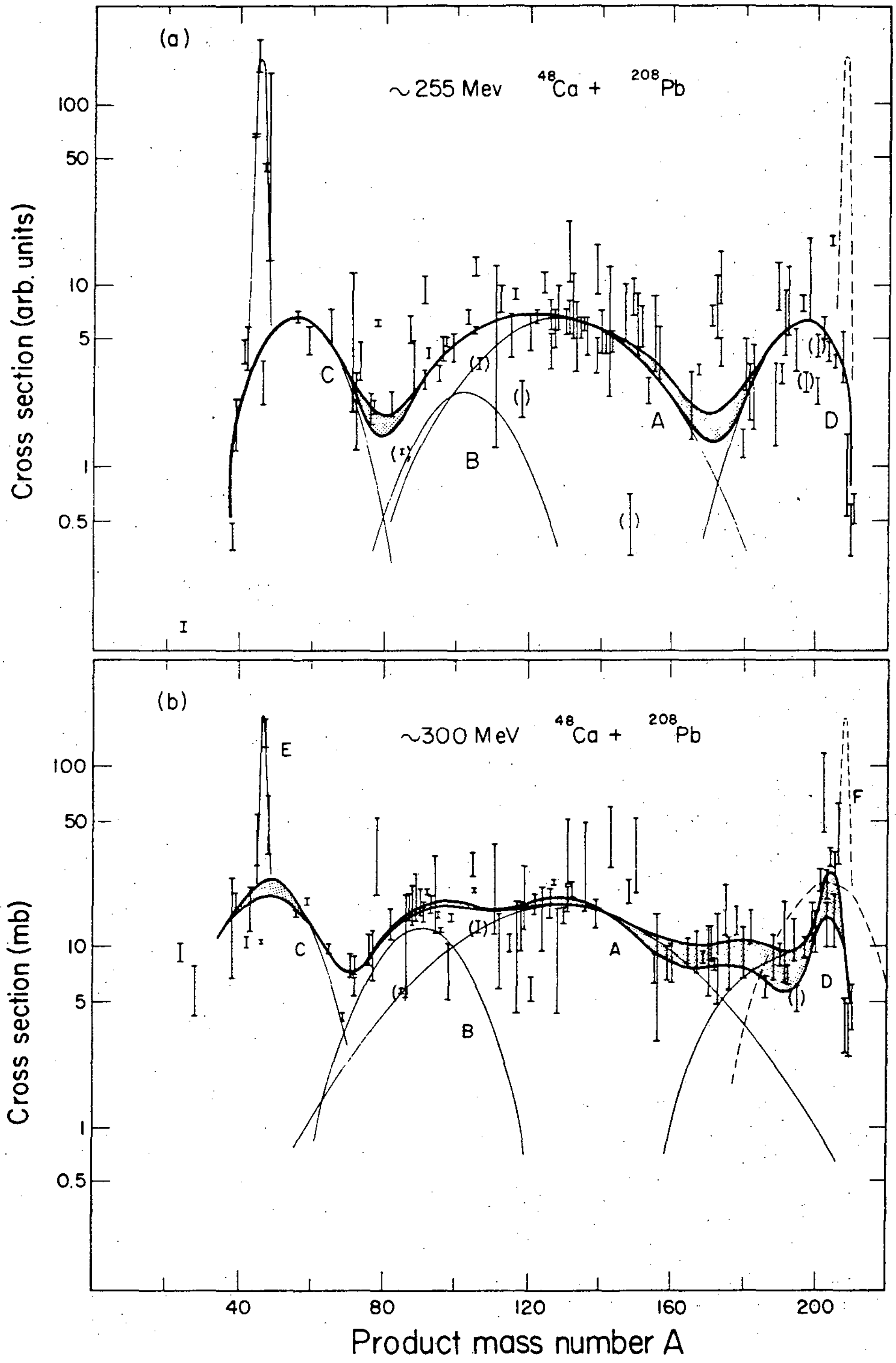

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Fig. 1

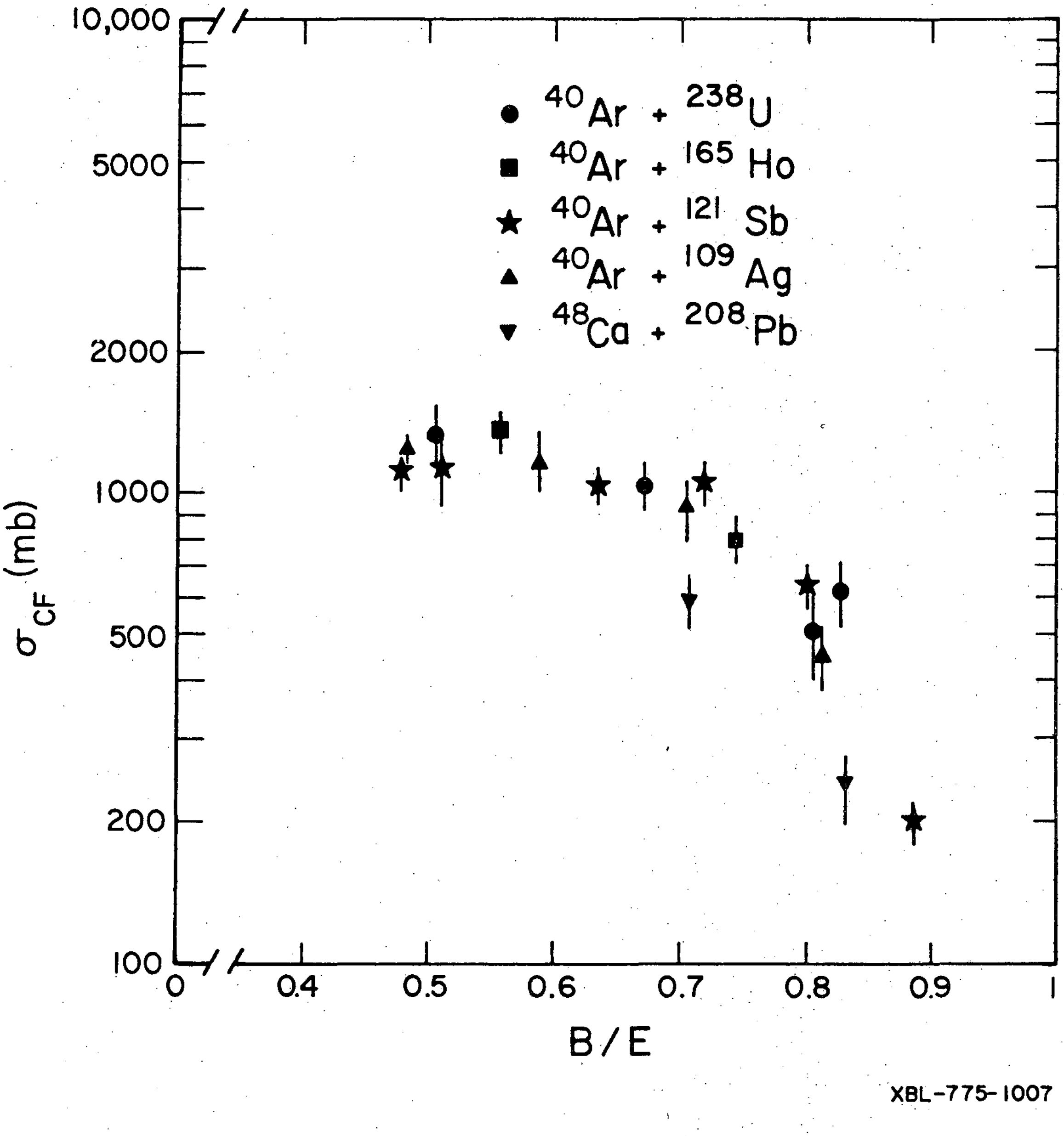
10,000
5000
2000
1000
500
200
100
0
0.4
0.5
0.6
0.7
0.8
0.9
1
σ_{CF} (mb)
B/E
● ^{40}Ar + ^{238}U
■ ^{40}Ar + ^{165}Ho
★ ^{40}Ar + ^{121}Sb
▲ ^{40}Ar + ^{109}Ag
▼ ^{48}Ca + ^{208}Pb
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Fig. 2

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720