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Publication Date
1977-06-01

Submitted to Physical Review Letters

LBL-6539
Preprint c.1

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June 1977

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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

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June 1977

ABSTRACT

The results of radiochemical 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 a factor of ~2 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. Implications for superheavy element production with ^{48}Ca induced reactions are discussed.

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Concurrent with recent attempts to produce superheavy elements (SHE) in reactions involving the bombardment of highly fissionable heavy element targets such as ^{248}Cm with doubly-magic, neutron rich ^{48}Ca,[1] and in an attempt to understand better the reactions of this unique projectile, 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 for the first time the finding that the complete fusion cross section is reduced twofold in a doubly-magic projectile-target system compared to similar cross sections for non-magic systems. We also combine our results with the parallel work of Ghiorso et al.,[2] who measured the evaporation residue yields from this reaction, to draw implications for the production of SHE using ^{48}Ca induced reactions.

Isotopically pure ^{208}Pb targets of thickness 42-45 mg/cm^2 were irradiated with beams of ^{48}Ca ions of incident energy 303 and 408 MeV from the SuperHILAC of the Lawrence Berkeley Laboratory. The lower energy bombardment lasted 60 minutes with an average intensity of $\sim 9.3 \times 10^{13}$ particles/minute while the higher energy bombardment lasted for 108 minutes with an average intensity of $\sim 4.7 \times 10^{13}$ 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,[3] 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 resulting mass distributions are shown in Figures 1(a) and 1(b). Integration of these charge dispersions to correct for unmeasured yields increases, on the average, the calculated isobaric yield in a given region by a factor of ~2 over the measured partial cumulative and independent yields. However, some individual yields can be multiplied by factors up to ~6 because they represent only ~15% of the total isobaric yield.

The relative contributions to the measured mass distributions from complete fusion-fission and the fission of quasi-$Pb^{\ddagger}$ species were evaluated by a non-linear least squares fitting to the measured data of our best estimates for the shapes of the mass distributions from these processes. The shape of the mass distribution from the fission of quasi-Pb products was estimated by using mass distributions from charged particle induced fission.[4] The shape of the mass distribution from the fission of the No compound nucleus in the lower energy reaction was constructed from the measured ^{252}No spontaneous fission mass distribution,[5] and the mass distributions from the compound nucleus fission from the reaction of light ions (^{4}He, ^{12}C, ^{16}O) with U and Pu targets.[6] The shape of the mass distribution from the higher energy complete fusion-fission reaction is thought to be a symmetric Gaussian shape with a FWHM ~70 amu.[7] The shapes of the fission mass distributions were corrected for recoil losses (a ~20% to ~2% correction for A=40 to 160, respectively).

Figure 1(a) shows the results of the best least squares component analysis of the mass distribution for the low energy reaction. The curve labeled A represents fusion-fission, component B the quasi-Pb fission and component C the light deep inelastic mass distribution. Component B(÷2) plus the heavy deep inelastic peak, component D, is approximately equal to component C, as expected. However, our main interest is in the value of the complete fusion cross section, σ_{CF}, component A(÷2). Because of the relatively clean separation of the complete fusion-fission and deep inelastic components the value of σ_{CF} is not strongly dependent on the deep inelastic component. We can calculate the absolute magnitude of the complete fusion-fission cross section by knowing what fraction of the measured total reaction cross section, σ_R, it represents. It has been shown[3] in previous work of this type that the observed σ_R agrees with the mean geometrical reaction cross section, $\bar{\sigma}_R$. The area under curve A in Figure 1(a) represents 19±2% of the total measured reaction cross section. The mean geometrical reaction cross section, $\bar{\sigma}_R$, can be calculated from the equation:

$$\bar{\sigma}_R = \pi R^2 \left\{ \frac{\int_B^E (1-B/E)dE}{(E-B)} \right\} = 979 \text{ mb}, \qquad (1)$$

where the interaction barrier, B, is 212 MeV, the incident projectile energy (lab), E, is 303 MeV and the interaction radius, R, is 13.7 fm. This gives σ_{CF}=190 ± 20 mb and an effective projectile energy in the thick target of 255 MeV.

The component analysis of the mass distribution from the high energy reaction is not as clear-cut. Figure 1(b) shows this mass distribution as well as the best least squares fit to the distribution using the same shape for the deep inelastic component as in Figure 1(a). A range of values of σ_{CF} (from 250 to 530 mb) was obtained by varying the shape of the deep inelastic component from one that minimized σ_{CF} to one that maximized σ_{CF} while maintaining a meaningful fit to the data. Reasoning at the 95% confidence level, we can say that $\sigma_{CF} = 300^{+230}_{-50}$ mb. The measured reaction cross section is 1600 ± 310 mb, in agreement with the calculated value (using equation (1)) of $\bar{\sigma}_R$=1710 mb and corresponding to an effective projectile energy of 300 MeV.

These values of σ_{CF} seemed low compared to values obtained for ^{40}Ar induced reactions.[8-10] 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[8-10] versus the parameter B/E, the laboratory interaction barrier divided by the effective laboratory energy of the projectile. Glas and Mosel[11] have predicted the general behavior of the complete fusion cross sections that is seen in Figure 2. The dashed curve in Figure 2 is the calculated value of σ_{CF} as a function of energy for the reaction of $^{40}Ar + ^{165}Ho$, and the solid curve for the reaction of $^{48}Ca + ^{208}Pb$, using the Glas-Mosel approach.[11,12] As shown in Figure 2 a plot of σ_{CF} versus B/E for a common projectile with several targets defines a common curve. This agreement comes about because of the slow variation of σ_{CF} with target A (varies $\sim A^{1/3}_{target}$) and the compression caused by the logarthmic scale.

Figure 2 presents a simple method for the comparison of values of σ_{CF} for a given projectile with those that would be expected for ^{40}Ar projectiles, essentially independent of target. On this basis we conclude that the value of σ_{CF} for the $^{48}Ca + ^{208}Pb$ system is a factor of ~2 lower than that found for ^{40}Ar induced reactions, with non-magic targets, at comparable energies. We also show that the complete fusion cross section is smaller than the values for the $^{48}Ca + ^{208}Pb$ reaction predicted by the Glas-Mosel approach. Such an effect can perhaps be attributed to a smaller critical radius arising from both partners in the reaction being doubly-magic nuclei.[11] Additional evidence for this conclusion comes from the reaction of ^{40}Ar with magic ^{209}Bi,[13] where the value of σ_{CF} was found to be ~600 mb, a value that is below the ~800 mb expected for the B/E value of 0.74, but not as depressed as those values found for $^{48}Ca + ^{208}Pb$. This finding of a depressed fusion cross section for the $^{48}Ca + ^{208}Pb$ 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.

In connection with our SHE research program, our ultimate aim is to evaluate the evaporation residue cross sections for ^{48}Ca induced reactions. As an initial attempt to predict these cross sections we have used the results of this work and the two studies of evaporation residue products by Ghiorso et al., $^{48}Ca + ^{208}Pb$[2] and $^{40}Ar + ^{208}Pb$.[14] Ghiorso et al. have found that the peak cross section for neutron evaporation residues, σ_{ER}, for the reaction $^{208}Pb(^{48}Ca,2n)$ is ~3 microbarns, whereas the peak cross section for the reaction $^{208}Pb(^{40}Ar,3n)$ is 15 nanobarns. Using a modified version of the statistical evaporation code OVERLAID ALICE[15] with the inclusion of realistic fission barriers[16] and a fitted level density parameter ratio a_f/a_n value of 1.1 we are able to reproduce the measured σ_{ER}/σ_{CF} ratio and to understand these results in terms of the differences in the fission barriers and excitation energies of the nuclei produced. This encourages us to extend these calculations with these "calibrated" input parameters to the $^{48}Ca + ^{248}Cm$ system. Such an application yields a value of σ_{ER} as large as $\sim 10^{-32}$ cm^2 at E_{lab}=240 MeV and σ_{ER} $\sim 10^{-36}$ cm^2 at E_{lab}=255 MeV for the $^{248}Cm(^{48}Ca,xn)$ reaction with the predicted element 116 ground state fission barriers.[16] The reported study of the $^{48}Ca + {}^{248}Cm$ reaction[1] was performed at an average laboratory bombarding energy of 255 MeV and set upper limits on the production cross section for SHE's at $\sim 10^{-35}$ cm^2. This result is consistent with our calculation. Although the estimated $\sigma_{ER} \sim 10^{-32}$ cm^2 may well be overoptimistic, it does give us some hope for further attempts to synthesize SHE with low energy (E~240 MeV) ^{48}Ca bombardments of ^{248}Cm, assuming the complete fusion cross section does not become vanishingly small at this near barrier energy.[17]

We would like to thank A. Ghiorso and J. M. Nitschke for their assistance in carrying out the ^{48}Ca bombardments, B. F. Gavin for the development of the ^{48}Ca ion source and the SuperHILAC crew for providing and maintaining the ^{48}Ca beam. We wish to acknowledge the assistance of Diana Lee in analyzing the γ-ray spectra. One of us (WDL) gratefully acknowledges sabbatical leave support from Oregon State University.

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*Work supported in part by the Division of Physical Research, U.S. Energy Research and Development Administration.

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‡We use the term "quasi-Pb" to describe the distribution of target-like products produced by the deep inelastic multinucleon transfer reaction between projectile and target.

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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. The dashed and solid curves are the calculated values of σ_{CF} for ^{40}Ar + ^{165}Ho and ^{48}Ca + ^{208}Pb, respectively.

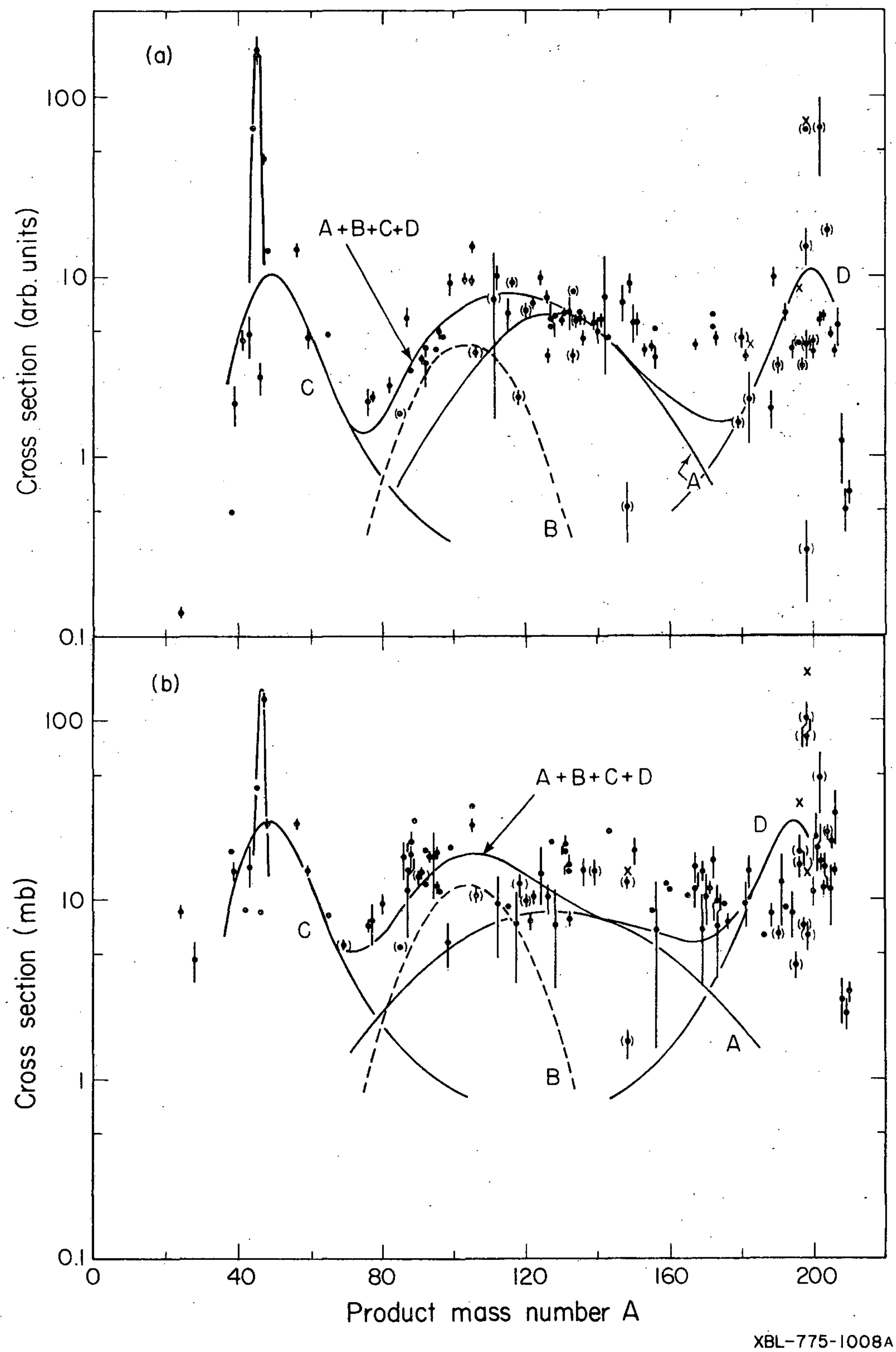
(a)
A+B+C+D
C
B
A
D
Cross section (arb. units)
100
10
1
0.1
(b)
A+B+C+D
C
B
A
D
Cross section (mb)
100
10
1
0.1
0
40
80
120
160
200
Product mass number A
XBL-775-1008A

Fig. 1

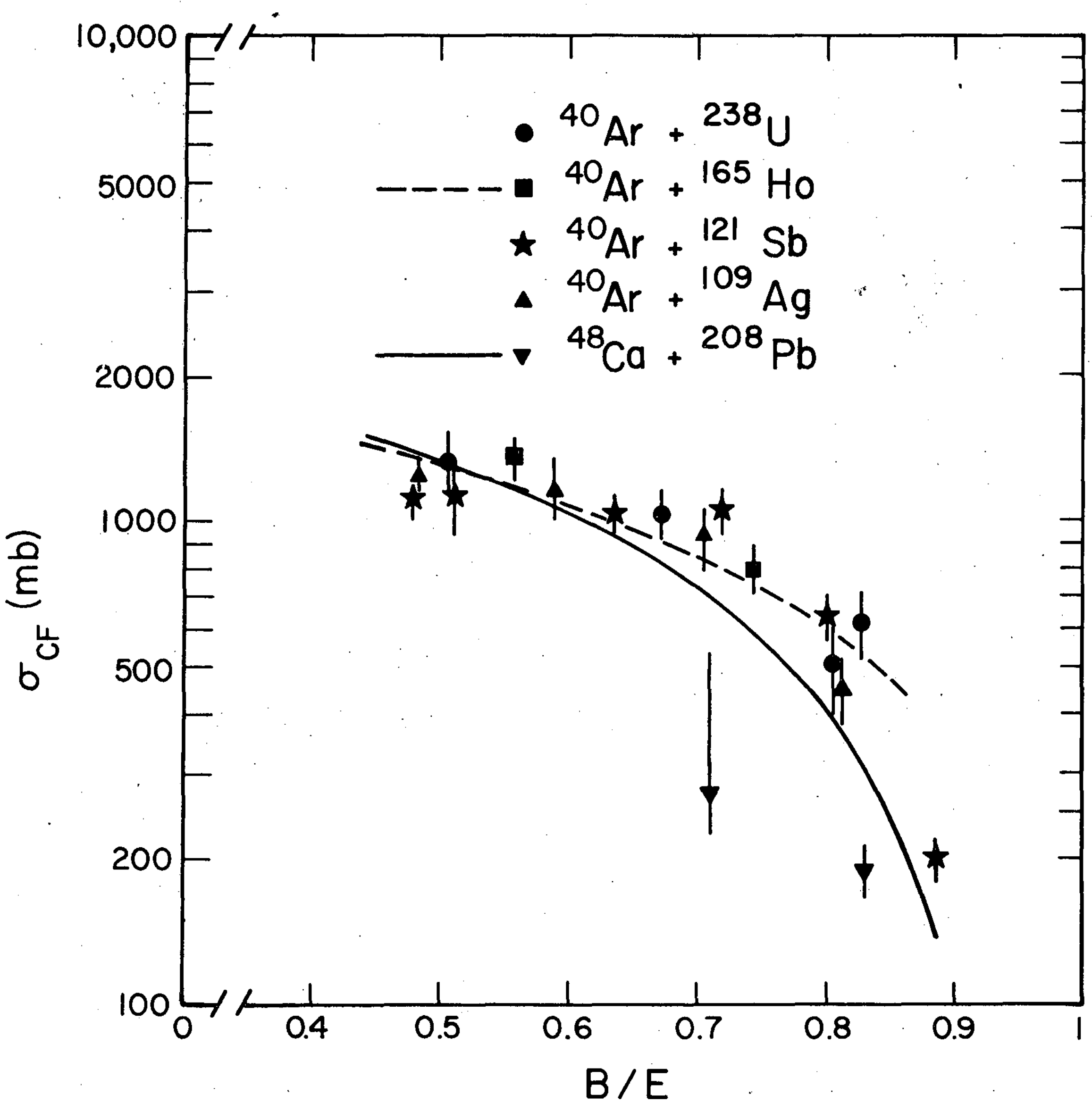
10,000
5000
2000
1000
500
200
100
0
0.4
0.5
0.6
0.7
0.8
0.9
1
40Ar + 238U
40Ar + 165 Ho
40Ar + 121 Sb
40Ar + 109 Ag
48Ca + 208 Pb
σCF (mb)
B/E
XBL-775-1007A

Fig. 2

This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

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