[1]W. Kloet and J. Tjon, Phys. Lett. 49B, 419 (1974).
[2]A. D. Jackson, A. Lande, and D. O. Riska, Phys. Lett. 55B, 23 (1975).
[3]J. Borysowicz and D. O. Riska, Nucl. Phys. A254, 301 (1975).
[4]The form factors F_1 in (1) are a consequence of using pseudovector πN coupling; with pseudoscalar coupling they would be replaced by the corresponding magnetic form factors G_M.
[5]J. W. Negele, Phys. Rev. C 1, 1260 (1970).
[6]J. W. Negele and D. Vautherin, Phys. Rev. C 5, 1472 (1972).
[7]M. Gari, H. Hyuga, and J. G. Zabolitzky, Nucl. Phys. A271, 365 (1976).
[8]M. Radomski and D. O. Riska, Nucl. Phys. A274, 428 (1976).
[9]G. J. C. VanNiftrik, Nucl. Phys. A131, 574 (1969).
[10]H. Euteneur, J. Friedrick, and N. Voegler, Phys. Rev. Lett. 36, 129 (1976).
[11]B. Frois *et al.*, Phys. Rev. Lett. 38, 152, 576(E) (1977).
[12]W. Bertozzi, J. Friar, J. Heisenberg, and J. W. Negele, Phys. Lett. 41B, 408 (1972).
[13]J. L. Friar and J. W. Negele, in Proceedings of the 1977 Bates Linac Summer Study, edited by A. Bernstein (unpublished).
[14]J. W. Negele, Phys. Rev. Lett. 27, 1291 (1971).
[15]J. W. Durso, A. D. Jackson, and B. J. Verwest, Nucl. Phys. A282, 404 (1977).
[16]D. O. Riska and M. Radomski, Phys. Rev. C 16, 2105 (1977).

Resonant Backward-Angle Heavy-Ion Elastic Scattering

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We observe strong structure in the excitation functions of $^{12}C + ^{28}Si$ backward-angle scattering. Angular distributions at the peaks of the elastic excitation function are of the form $P_J^2(\cos\theta)$ [approximately $J = 15$ ($E_{c.m.} = 23.3$ MeV), $J = 18$ ($E_{c.m.} = 26.0$ MeV), and $J = 18$ ($E_{c.m.} = 30.2$ MeV)]. These results appear to be inconsistent with existing theoretical descriptions of anomalous backward-angle heavy-ion elastic scattering in this mass region.

Systematic studies of $^{16}O + ^{28}Si$ elastic scattering[1] and $^{12}C + ^{28}Si$ elastic scattering[2,3] have shown anomalous midenergy ($E_{c.m.} \sim 30$ MeV), midangle ($40° \lesssim \theta_{c.m.} \lesssim 90°$) structure. Braun-Munzinger *et al.*[4] have measured the elastic angular distribution for the $^{16}O + ^{28}Si$ system out to $\theta_{c.m.} = 180°$ and found large oscillatory cross sections. Theoretical interpretations of these results have included Regge poles,[4] a variable-moment-of-inertia rotational band,[5] and surface transparent optical potentials with coupled-channel effects.[6] These and other interpretations are presented elsewhere.[7] We have measured the backward-angle angular distribution of the system $^{12}C + ^{28}Si$ over the energy range (17.5 MeV $\lesssim E_{c.m.} \lesssim$ 33 MeV). Our observations are apparently inconsistent with all of the existing theories of the oscillatory backward-angle enhancements of $^{12}C + ^{28}Si$ and $^{16}O + ^{28}Si$ elastic scattering.

The ^{28}Si beam of the University of Rochester MP tandem was used to bombard carbon and beryllium foils of an approximate thickness of 100 $\mu g/cm^2$. The elastically scattered C or Be ions were detected at forward angles corresponding to c.m. angles (in the ^{28}Si target system) between 120° and 175°. Complete mass, Z, and charge-state identification of the reaction products was provided by the Enge split-pole Rochester heavy-ion detector system.[8] Several angles could be measured simultaneously because the angle of incidence is determined for each event. Absolute normalizations were obtained by monitoring the scattering from a thin layer of Au which was evaporated on the targets.

We have measured backward angular distributions for the $^{12}C + ^{28}Si$ at 28 energies in the range 17.5 MeV $\leqslant E_{c.m.} \leqslant$ 33 MeV. At each incident energy the data are averaged over about ±200 keV because of the thickness of the target. Examples of the data are shown in Fig. 1. At all energies a rise in cross section is seen as $\theta_{c.m.}$ increases. The observed ratio of $\sigma/\sigma_R \sim 10^{-2}$ is about two orders of magnitude higher than expected with use of systematic potentials of Refs. 1 and 2. Furthermore, at certain c.m. energies the data show regular oscillations which can be fitted with the square of a Legendre polynomial. These features were also seen in the $^{16}O + ^{28}Si$ system.[4] However, at intermediate energies the oscillations in the angular distributions are irregular or weak and have a lower overall magnitude. This latter feature is best observed in Fig. 2

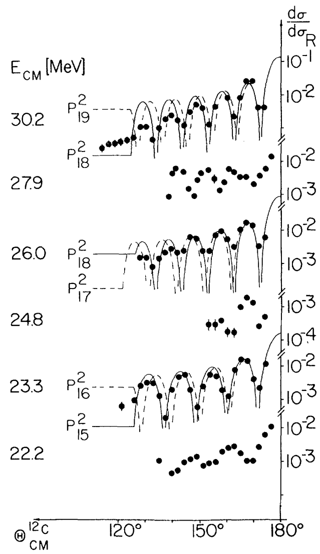

FIG. 1. Angular distributions for the elastic scattering of $^{12}C + {}^{28}Si$ at the c.m. energies indicated. The displayed data are a selected sample of the 28 angular distributions which were measured.

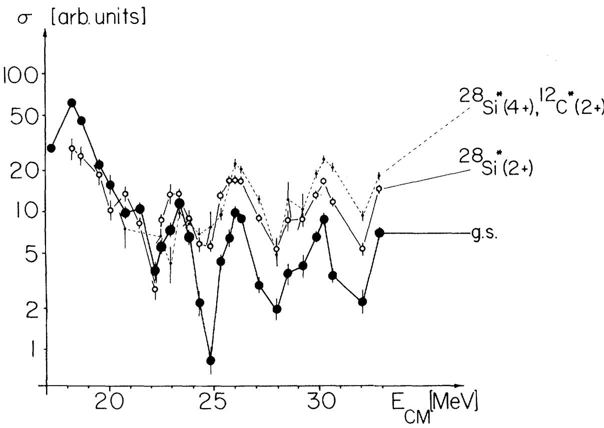

FIG. 2. Excitation functions for the integrated (153° $\leq \theta_{c.m.} \leq$ 175°) $^{12}C + {}^{28}Si$ elastic and inelastic scattering.

which plots the integrated backward-angle cross section as a function of incident energy. Notice the large (~ 10/1) peak-to-valley elastic ratio and the narrow width ($\lesssim$ 2 MeV). Structure is seen in the excitation functions in both the elastic and inelastic scattering. At and near the peaks of these "resonances" we observe (see Fig. 1) regular, highly oscillatory angular distributions; at the minima, irregular or weakly oscillatory distributions are seen. Figure 1 indicates that the angular distributions near the peaks in the excitation function have maxima which correspond to the square of the Legendre polynomial indicated. The grazing partial wave at each of these resonant energies can be determined from optical potentials which fit the forward-angle data.[2,3] This technique yields $E_{c.m.} = 23.3$ MeV, $J_{expt} = 15$, $J_{graz} = 16$; $E_{c.m.} = 26.0$ MeV, $J_{expt} \simeq 18$, $J_{graz} = 18$; $E_{c.m.} = 30.2$ MeV, $J_{expt} \simeq 18$, $J_{graz} = 21$. These results should be compared with the $^{16}O + {}^{28}Si$ system where, at $E_{c.m.} = 35.0$ MeV, the angular distribution followed a $P_J{}^2(\cos\theta)$ form with J within one unit of the grazing partial wave. Notice that the upper two resonances have angular distributions with almost identical periodicities; at the lowest resonance, the angular distribution has a quite different J.

We have measured $^{13}C + {}^{28}Si$ backward angular distributions at five energies between 23 MeV $< E_{c.m.} <$ 32.8 MeV. Similarly the $^{9}Be + {}^{28}Si$ system has been studied at $E_{c.m.} = 24.3$ MeV at both forward and backward angles. In both cases the integrated elastic cross sections are suppressed by one order of magnitude compared with the $^{12}C + {}^{28}Si$ system. Furthermore, strong oscillations are not observed in most cases, and the angular distributions have a minimum at 180°. These data along with all the $^{12}C + {}^{28}Si$ angular distributions will be published at a later date. Similarity of our data to other systems should be noted. For example, the resonant nature of "light" heavy-ion systems such as $^{12}C + {}^{12}C$ and $^{12}C + {}^{16}O$ is well established.[9] Recently, resonances were reported[10] in the $\theta_{c.m.} = 177°$ excitation function of $^{16}O + {}^{24}Mg$ elastic scattering although angular distributions were not measured. Anomalous backward-angle elastic scattering of α particles from calcium isotopes is also a well-known phenomenon.[11]

Our results provide severe restraints on possible theoretical explanations of the large backward-angle cross sections seen in the $^{12}C + {}^{28}Si$ system. Regge poles corresponding to the surface partial wave[4] seem unlikely since we observe nearly the same $[\sim P_{J=18}{}^2(\cos\theta)]$ angular distribution at two incident energies separated by 4 MeV in the c.m. system while 3 MeV lower a $P_{15}{}^2(\cos\theta)$ distribution is found. This observation probably rules out any explanation involving a simple band of states. The observation of a highly structured excitation function, i.e., "resonances," probably rules out a direct-reaction (optical-model of distorted-wave Born-approximation) explanation, since such models would be expected to yield excitation functions which vary smoothly with energy. Further theoretical and experimental work is needed to understand the nature and origin of the enhanced oscillatory backward-angle heavy-ion elastic scattering in this mass region.

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[1]J. G. Cramer, R. M. DeVries, D. A. Goldberg, M. S. Zisman, and C. F. Maguire, Phys. Rev. C 14, 2158 (1976).

[2]R. M. DeVries, D. A. Goldberg, J. W. Watson, M. S. Zisman, and J. G. Cramer, Phys. Rev. Lett. 39, 450 (1977).

[3]C. M. Cheng, J. V. Maher, W. Oelert, and F. D. Snyder, to be published.

[4]P. Braun-Munzinger, G. M. Berkowitz, T. M. Cormier, C. M. Jachcinski, J. W. Harris, J. Barrette, and M. J. LeVine, Phys. Rev. Lett. 38, 944 (1977).

[5]J. G. Cramer, J. C. Wiborg, Y.-d. Chan, K.-l. Liu, M. S. Zisman, B. D. Cuengco, W. G. Lynch, and R. T. Puigh, to be published.

[6]T. Udagawa, in *Proceedings of the International Conference on Nuclear Structure, Tokyo, Japan, 1977,* edited by The Organizing Committee (International Academic Printing Co. Ltd., Tokyo, 1977).

[7]Proceedings of the Symposium on Heavy-Ion Elastic Scattering, University of Rochester, 1977, edited by R. M. DeVries (to be published).

[8]D. Shapira, R. M. DeVries, H. W. Fulbright, J. Tōke, and M. R. Clover, Nucl. Instrum. Methods 129, 123 (1975).

[9]R. Siemssen, in *Proceedings of the Symposium on Heavy-Ion Scattering, Argonne National Laboratory, 1971,* edited by R. H. Siemsse (Argonne National Laboratory, Argonne, Ill., 1971).

[10]P. Chevallier, D. Disdier, S. M. Lee, V. Rauch, G. Rudolf, and F. Scheibling, in *Proceedings of the International Conference on Nuclear Structure, Tokyo, Japan, 1977,* edited by The Organizing Committee (International Academic Printing Co. Ltd., Tokyo, 1977).

[11]G. Gaul, H. Ludecke, R. Santo, H. Schmeing, and R. Stock, Nucl. Phys. A137, 177 (1969).

Yet More Complexity in Fission: Barriers for Nuclei with $N = 150-154$

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Fission probabilities are presented for a series of Pu, Cm, and Cf nuclei with neutron numbers, N, in the range of 150–154. Results show that the fission thresholds are slowly varing with N and Z for $N = 150-153$ but there is a strong decrease in the threshold for $N = 154$. For ^{252}Cf ($N = 154$) the results indicate broad, strong resonances at ~5.0 and 5.4 MeV and suggest the breakup of the first axially asymmetric saddle into two barriers with large $\hbar\omega$.

As experimental and theoretical studies of fission barrier properties have become more complete, they have tended to reveal an increasing complexity in the potential energy surface associated with the fission process. Early attempts to compare experimental and theoretical barriers led to the discovery that for most actinide nuclei the lowest two saddle points had axially and mass deformed shapes.[1,2] More recent experiments have strongly supported the postulate that the second mass-asymmetric barrier has two components[3-5] in the Ra–Th region and that there exists an additional axially asymmetric second barrier[6] which provides a slightly higher, parallel path to fission for nuclei in the Ra–U region. In addition to these new general features, experiments[7] in the heavy actinides have shown a very abrupt change in the first barrier height in the region of neutron numbers $N = 152-154$.

In this Letter we present new data on fission probabilities for a series of Pu, Cm, and Cf isotopes which show relatively constant fission thresholds for $N < 153$ followed by an approximately 1-MeV decrease as N increases from 153 to 154. A more surprising result is that for ^{252}Cf fission ($N = 154$) there appear to be two very strong transmission resonances and the second and strongest one has an angular correlation suggesting $K > 0$. These resonances have the largest fission probability ever observed for a fission resonance and this is the first case of a resonance where anisotropy measurement suggest $K > 0$.

The new results came from studies of (t, pf), (d, pf), and $(p, p'f)$ reactions on targets of ^{244}Pu, ^{246,248}Cm, and ^{250}Cf forming compound fissioning systems of ^{246}Pu, ^{246,248}Cm, and ^{250,251,252}Cf. The experimental setup and data analysis procedures

