Static Nuclear Deformation and the Total Reaction Cross Section*

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An empirical study is made of the total reaction cross sections for ^{4}He reactions with ^{208}Pb, ^{209}Bi, ^{233}U, and ^{237}Np. Systematic differences are revealed that are attributed to the effects of nuclear deformation. This behavior can be accounted for by a reduction of the average interaction barrier by 0.3 to 0.6 MeV or by an increase in the width of the spectrum of barriers by 0.4 to 0.7 MeV.

Calculated values of the total reaction cross section (σ_R) depend on the deformation of each of the colliding nuclei.[1-4] The calculations, from several models of varying sophistication, indicate that the sensitivity of σ_R to deformation is very small for energies greater than the interaction barrier, but appreciable for lower energies.[1-4] One or both reaction partners may exhibit static nuclear deformation or, in addition, dynamic shape changes can be induced during the collision act. Several theoretical investigations lead to the expectation that dynamic effects are very small.[5,6] Static deformation, however, is expected to lead to decidedly enhanced reaction cross sections at low energies because of the lower interaction barrier for collisions near the polar axis.[1-3]

Previous studies of the available experimental data have not been able to isolate this effect.[1-3,7] In this paper we present an empirical approach to this problem that does indicate significant effects of static deformation on σ_R. We use the experimental data of Barnett and Lilley[8] for the near-spherical nuclei ^{208}Pb and ^{209}Bi, those of Freiesleben and Huizenga[3] and Lin[9] and Fleury *et al.*[10] for the statically deformed nuclei ^{233}U and ^{237}Np. The results are, of course, completely dependent on the accuracy of the experimental data—in particular, the effective beam energies. The relevant experimental data from Refs. 3 and 8–10 were obtained with modern techniques for control of beam energy at Van de Graaff accelerators.

We have used the equations for penetration of a real parabolic barrier to fit measured total reaction cross sections. The transmission coefficient $T(l,E)$ for the partial wave l is given by the Hill-Wheeler[11] formula

$$T(l,E)=[1+\exp\{2\pi(E_l-E)/\hbar\omega_l\}]^{-1}, \quad (1)$$

where E is the incident energy (c.m.). The effective potential barrier height E_l is given by

$$E_l=V_N(R_l)+V_C(R_l)+\hbar^2 l(l+1)/2\mu R_l^2, \quad (2)$$

with R_l the radial distance corresponding to the maximum and with V_N and V_C the nuclear and Coulomb potentials. Wong[2] has derived a very simple expression for the total reaction cross section:

$$\sigma_R=(R_0^2/2)(\hbar\omega_0/E)\times\ln[1+\exp\{2\pi(E-E_0)/\hbar\omega_0\}], \quad (3)$$

with the approximation that the curvature $\hbar\omega_l$ and radius R_l are independent of l (i.e., $\hbar\omega_1=\hbar\omega_0$ and $R_l=R_0$).

Vaz and Alexander[7] have modified this expression by consideration of a uniform distribution of barrier heights between $\overline{E}_0-\Delta$ and $\overline{E}_0+\Delta$.[12] With this modification they have analyzed and systematized all the available reaction cross sections in terms of the four parameters $\overline{E}_0$, R_0, $\hbar\omega_0$, and Δ. No clear variations could be determined for the empirical parameters $\hbar\omega_0$ and Δ; values of ≈ 4 MeV and ≈ 3 MeV, respectively, provide good fits to σ_R for $E\gtrsim\overline{E}_0$. For ^{4}He projectiles $\overline{E}$ and R_0 are well fitted by the following expressions:

$$E_0=2Ze^2/R_e \quad (4)$$

with

$$R_e=r_e A^{1/3}+2.53 \text{ fm}, \quad (5)$$

and

$$R_0=r_0 A^{1/3}+2.53 \text{ fm}. \quad (6)$$

The empirical value of r_0 (1.41 fm) seems to be essentially independent of Z. The empirical values of r_e vary rather slowly with Z.[7]

Our knowledge of the shape and height of the interaction barrier from theory or from other measurements (i.e., elastic scattering) is not yet well enough developed to give us precise values

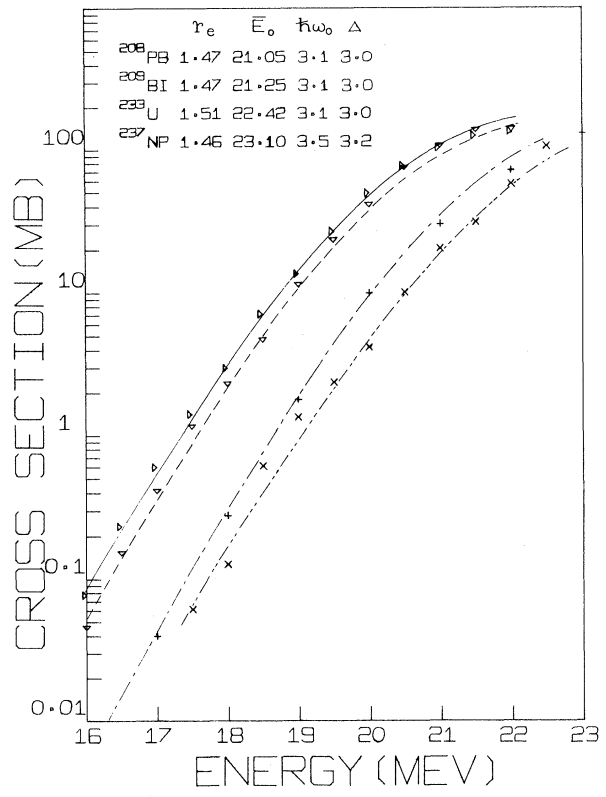

FIG. 1. The total reaction cross section σ_R versus laboratory energy for ^{4}He reactions with four targets. Data are from Refs. 3, 8, 9, and 10. Data points are indicated as follows: ^{208}Pb, ▷; ^{209}Bi, ▽; ^{233}U, +; ^{237}Np, ×. Calculated values of σ_R are given by the lines with "best-fit" parameters as indicated. In these fits r_0 was fixed at 1.41 fm and $\bar{E}_0$, $\hbar\omega_0$, and Δ were free parameters.

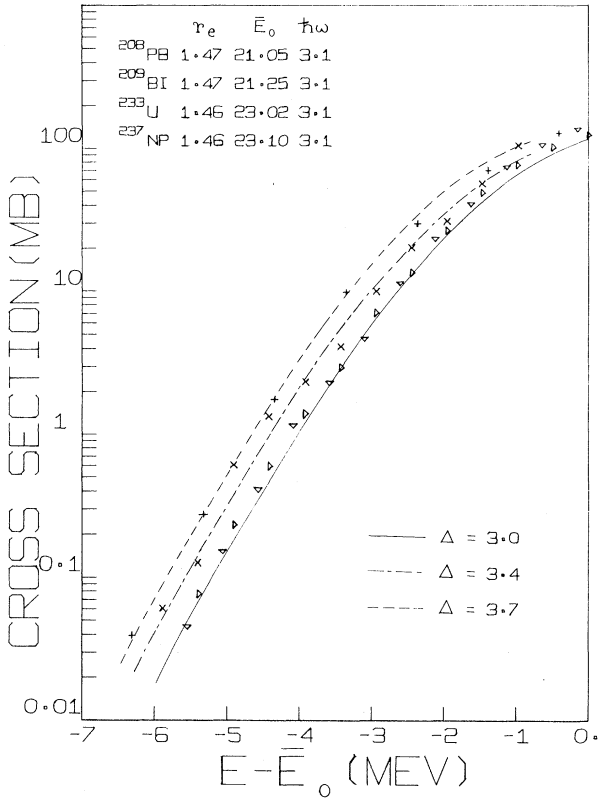

FIG. 2. σ_R versus $E-\bar{E}_0$ (c.m.) with $\bar{E}_0$ for all systems fixed to those indicated by the reference systems ^{208}Pb and ^{209}Bi. ($r_e = 1.47$ for ^{208}Pb and ^{209}Bi; $r_e = 1.46$ for ^{233}U and ^{237}Np). The solid, dashed, and dot-dashed lines were calculated with Δ values as indicated ($\hbar\omega_0$ and r_0 fixed at 3.1 MeV and 1.41 fm). Symbols for data points are as in Fig. 1.

of r_e, r_0, $\hbar\omega_0$, and Δ. Freiesleben and Huizenga[3] have employed independently estimated potential parameters in several formulations, in an attempt to describe $\sigma_R(E)$ and identify the effect of static deformation. They were unable to obtain a good fit to σ_R at low energies (with no free parameters). Even with barrier heights fitted to experiment no effect of deformation was apparent.

We have taken the empirical route in the examination of the reactions of ^{4}He with ^{208}Pb, ^{209}Bi, ^{233}U, and ^{237}Np. (The data for the first three systems were also examined in Ref. 3. New data for ^{237}Np are now available.[9]) First we fitted the σ_R data for all systems with the three free parameters r_e (or $\bar{E}_0$), $\hbar\omega_0$, and Δ; r_0 was fixed at 1.41 fm.[7] The quality of fit and the parameters used are shown in Fig. 1. These values of $\bar{E}_0$ are somewhat larger than those obtained from analysis of elastic scattering measurements.[13] This difference may well be due to the models used —namely, the use of a single potential barrier ($\Delta \equiv 0$) in Ref. 13 and a spectrum of barriers here (finite Δ).

At first glance there is no clear systematic difference between the parameters for the near-spherical nuclei ^{208}Pb and ^{209}Bi and the deformed nuclei ^{233}U and ^{237}Np. However, the picture changes if we take the near-spherical nuclei as reference systems and then calculate σ_R for ^{233}U and ^{237}Np. Values of r_0, r_e, Δ, and $\hbar\omega$ from the reference systems are 1.41 fm, 1.47 fm, 3.0 MeV, and 3.1 MeV, respectively. The systematic variation of r_e with Z leads us to expect a change of -0.01 fm for r_e from the reference Z of 82, 83 to Z of 92, 93. The systematics give no indication of a change for $\hbar\omega_0$ or Δ. In Fig. 2 we replot σ_R against $E-E_0$ for the four systems. As R_0 is very nearly the same for all four, the data

points should follow the solid line calculated with parameters for the reference systems Pb and Bi [see Eq. (3)]. The observation from Fig. 2 is that σ_R for Np and U is 1.5 to 2 times as great as that for Pb and Bi ($E - E_0 < -2$ MeV).

In this formulation these systematic differences can be described either by a change in Δ (the width of the spectrum of barriers) or in $\bar{E}_0$ (the average barrier height). In Fig. 2 the dashed curves give fits to the data for U and Np with Δ allowed to vary from the reference value. Increases in Δ of 0.7 and 0.4 MeV give good fits for U and Np, respectively. Alternatively $\bar{E}_0$ (or r_e) can be allowed to vary with Δ, $\hbar\omega_0$, and r_0 fixed at the reference values. In Fig. 3 we show the convergence of the data resulting from decreases in $\bar{E}_0$ of 0.6 and 0.3 MeV, respectively, for U and Np. Wong[3] has estimated that target deformation in this region will raise r_e by ≈ 0.1 fm; Fig. 3 indicates an increase of 0.03 to 0.05 fm.

Our conclusions are as follows: Empirical comparison reveals systematic differences in the reaction cross sections for ^{4}He reactions with ^{208}Pb, ^{209}Bi, ^{233}U, and ^{237}Np. These differences are exhibited if potential parameters are obtained from the Pb and Bi systems and then used to calculate expected values of σ_R for U and Np. The values of σ_R for statically deformed Np and U seem to be enhanced by 1.5 to 2 times compared to the reference systems, Pb and Bi. This enhancement can be accounted for by a change in the half-width of the spectrum of barrier heights by 0.4 to 0.7 MeV or by a reduction of the average barrier by 0.3 to 0.6 MeV (or some combination).

The conclusion that we reach is that static deformation of one collision partner does affect the reaction cross section at low energies. The conclusion of Ref. 3 was that such an effect is not evident if one uses independently obtained parameters to describe the potential. We agree that our present models and our knowledge of the internuclear potential are not well enough developed to reveal such small effects. Thus, we conclude that semiempirical methods are most useful for systemization and characterization of the phenomena.

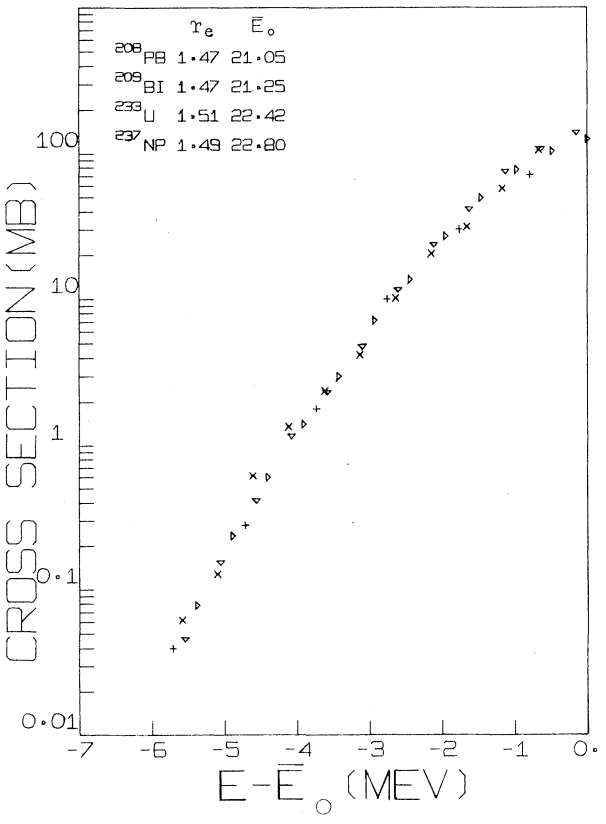

FIG. 3. σ_R versus $E-\bar{E}_0$ (c.m.) with $\bar{E}_0$ and r_e values as indicated. Values of r_0, $\hbar\omega_0$, and Δ fixed as 1.41 fm, 3.1 MeV, and 3.0 MeV, respectively.

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eters for $E < \bar{E}_0$.

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Element 106†

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We have produced element 106 by bombarding ^{249}Cf with ^{18}O ions accelerated by the SuperHILAC. The new nuclide ^{263}106, produced by the $(^{18}O, 4n)$ reaction, is shown to decay by α emission with a half-life of 0.9 ± 0.2 sec and a principal α energy of 9.06 ± 0.04 MeV to the known nuclide ^{259}Rf, which in turn is shown to decay to the known nuclide ^{255}No.

The identification of new elements at the upper end of the periodic table is especially difficult because of extremely low production rates and because there are large uncertainties in predicting their nuclear properties. For these reasons, positive identification requires some means of determining the atomic number directly. Among the proven methods are (1) measurement of distinctive K x rays[1,2] following α decay and (2) establishment of a genetic link between an α emitter of a new element and a previously identified daughter nuclide. Our identification of element 106 is based on the latter method because of its higher sensitivity. This method was also used in discovering α-emitting isotopes of rutherfordium (element 104)[3] and hahnium (element 105).[4] For element 106, we have carried this method one step further by demonstrating that the granddaughter [^{255}No, $t_{1/2} = 3$ min, $E_\alpha = 8.11$ MeV (57%)][5,6,1] is in the chain of α decay of ^{263}106. Thus, our proof for the atomic number of element 106 comes from demonstrating the following decay sequence: $^{263}106 \xrightarrow{\alpha} {}^{259}\mathrm{Rf} \xrightarrow{\alpha} {}^{255}\mathrm{No} \xrightarrow{\alpha}$.

These genetic relationships were established in two ways depending on whether ^{263}106 α particles escaped from their backing surface. (1) When these particles were detected leaving the surface, we observed with a certain probability in a time interval of 12 sec the α's of the 3-sec daughter ^{259}Rf ($E_\alpha = 8.77$ and 8.86 MeV) that also were directed outward; i.e., we observed the decay sequence $^{263}106 \xrightarrow{\alpha} {}^{259}\mathrm{Rf} \xrightarrow{\alpha}$. (2) When ^{263}106 α's were directed into the backing surface (and hence were not detected), the recoil energy imparted to the daughter nucleus allowed it to escape from the surface and to be implanted in the face of an opposing detector. Upon periodically moving these detectors away from the original sources, the α decay of daughter ^{259}Rf and the subsequent α decay of the granddaughter were observed; i.e., we detected the decay sequence $^{259}\mathrm{Rf} \xrightarrow{\alpha} {}^{255}\mathrm{No} \xrightarrow{\alpha}$. Considering the finite thickness (~1 μg/cm^2) of the NaCl deposits containing the ^{263}106 atoms, the considerable recoil energy required to transfer the observed number of daughter ^{259}Rf atoms to the detector faces could be furnished only by a preceding α emitter. We thus were provided with a second genetic linkage to ^{263}106 by α decay.

The ^{18}O beam from the SuperHILAC (average 3×10^{12} ions/sec) was wobbled electromagnetically to prevent localized overheating of the target, which was both edge-cooled by contact with a water-cooled copper block and gas-cooled by helium impinging on the aluminum backing (Fig. 1). The energy of the ^{18}O ions emerging from the target was determined by measuring the energy of these ions scattered from the target into a Si(Au) surface barrier detector placed at 30° to the beam axis.

The target was prepared by subliming 259 μg of ^{249}Cf as CfF_3 onto a 27-μg/mm^2 substrate of