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HEAVY-ION-INDUCED FISSION REACTIONS

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ABSTRACT

Fission-cross-section excitation functions were measured from near threshold to ~10 MeV/nucleon using heavy-ion beams from the Brookhaven National Laboratory three-stage Tandem Accelerator Facility. The systems studied included ^{210}Po formed in ^{12}C and ^{18}O induced reactions, ^{186}Os formed in ^{9}Be, ^{12}C, ^{16}O, and ^{26}Mg reactions, ^{158}Er formed in ^{16}O, ^{24}Mg, ^{32}S, and ^{64}Ni reactions. In addition the composite systems ^{204,206,208}Po formed with ^{16}O and ^{18}O projectiles were studied.

The measured fission excitation functions along with previous data from ^{4}He and ^{11}B bombardments for the ^{186}Os and ^{210}Po systems and recent data on the ^{200}Pb system are compared to predictions from a statistical model using recent fission-barrier calculations from A. Sierk. Comparisons of calculated and measured fission excitation functions show good overall agreement between data and calculations and between calculations with two different level-density functions. It is concluded that the barriers from Sierk give a good description of both the mass and angular momentum dependence of fission barriers in this region.

INTRODUCTION

There have been many studies[1] of fission probabilities in the actinides that have yielded a comprehensive mapping of fission-barrier parameters in this region. For lighter nuclei, fission barriers ($\ell = 0$) become large compared to neutron binding energies, but for large angular momenta fission can again become a dominant process due to the centrifugal lowering of the barrier. In this region the limited experimental results have been fit with various statistical models[2-10] utilizing primarily calculated fission barriers from the rotating liquid drop model of Cohen, Plasil, and Swiatecki[11] (CPS). In fits to fission cross sections it has generally been necessary to renormalize the CPS barriers by varying factors. A more recent angular-momentum-dependent barrier calculation by Sierk[12] has been shown[9] to give a good representation of data to the composite systems ^{153}Tb and ^{181}Re without the necessity for renormalizing the calculated barrier heights.

The purpose of the present experiment was to develop a representative set of fission-cross-section data, so that it would be possible to test both the mass and angular momentum dependence of fission barriers in the mass region $150 < A < 210$. Using these data a statistical model utilizing the barrier calculations of Sierk has been developed, and the sensitivity of the calculations to various input assumptions has been tested.

EXPERIMENTAL

The experimental setup is illustrated schematically in Fig. 1. Coincident fission fragments are detected in multiwire proportional counters[13] that yield two-dimensional-position signals and a fast signal. The time of flight for each fragment is determined using a start signal generated by a thin (~200 $\mu g/cm^2$) MWPC[14] that is placed close to the target. The electronic logic was set up so that events were recorded on magnetic tape whenever either STOP 1 or STOP 2 registered a pulse. Then position and analog signals were recorded on magnetic tape from all detectors.

Absolute differential cross sections were calculated using measured geometries and assuming Rutherford scattering in the monitor detectors. Total fission cross sections were calculated assuming an angular distribution proportional to $1/\sin\theta$. We estimate that the systematic uncertainty in relative measurements for a particular projectile-target combination is less than 5%. The absolute uncertainty in the measured cross sections is believed to have a systematic uncertainty of less than 10% (except that in all cases the $1/\sin\theta$ angular distribution is assumed).

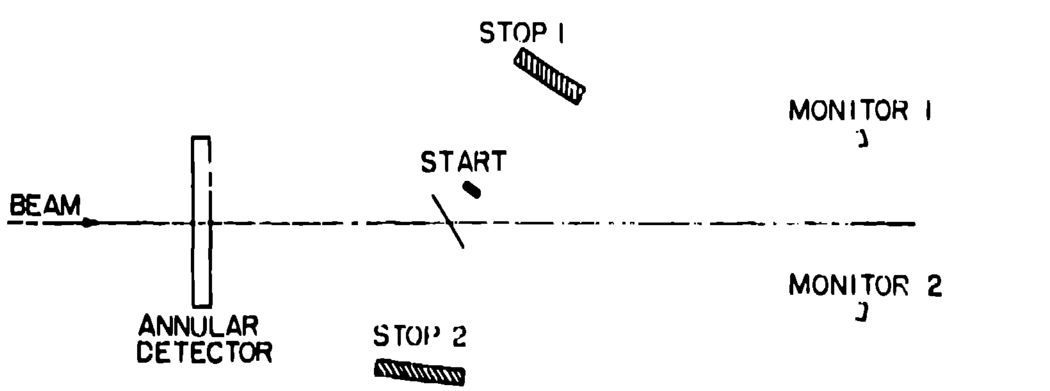

Fig. 1 Schematic diagram of the experimental setup.

THEORETICAL COMPARISONS

The major objective of this experiment was to provide a comprehensive data base of fission cross sections against which various theoretical models and concepts could be tested. In this context a model has been developed incorporating our current best estimates of the important physical parameters. This model uses Monte Carlo techniques and has been described in general technical terms previously.[15] This model necessarily involves both details of the compound nucleus formation process and the relative competition between fission and other modes in the compound nucleus decay process.

Any model of these processes must begin by estimating the fusion cross section as a function of angular momentum. We use the most recent model proposed by Bass[16] which gives a description of the fusion cross sections in this mass and energy region to an accuracy of the order ±10%. We have tested our model by comparing predictions with the recent measurements of Hinde et al.[10] where both evaporation residue and fission cross sections were measured for ^{19}F and ^{30}Si projectile reactions leading to ^{200}Pb.

In order to calculate the total fission cross section it is then necessary to estimate the branching ratios for fission relative to particle emission as a function of angular momentum and excitation energy. The basic inputs for such a calculation are the ground state masses of the relevant nuclei, the fission barriers as a function of mass and angular momentum, and the level densities at both the ground state and saddle-point deformations.

The fission barriers are taken from the calculations of Sierk[12] for the systems ^{158}Er, ^{186}Os, and ^{210}Po. These barriers are obtained from a model of rotating nuclei which incorporates effects due to the finite range of the nuclear forces and the diffuseness of the nuclear surface on the surface, Coulomb and rotational energies. Effects due to possible axially asymmetric deformations are also taken into account. When compared to previous calculations (CPS)[11] the results show a reduction in the fission barrier heights of the order of 15% for zero angular momentum and relatively larger effects at the high angular momenta which become important in these heavy ion reactions. Calculations based on a similar model but with a different shape parameterization have also been reported by Mustafa et al[17].

For the level densities two extreme models were used. First was a simple Fermi gas estimate that should be appropriate at high temperatures where shell and pairing effects have washed out. In this case excitation energies were measured from the appropriate liquid drop mass surface. In order to estimate the sensitivity to the form of the level density the fission cross sections were also calculated using microscopic level densities similar to the approach in the analysis of actinide fission probabilities.[1] Single-particle spectra from Nix[18] for Po and Os and from a Nilsson model calculation[19] for Er were used with the code of Morretto[20] to generate compound level densities.

RESULTS AND DISCUSSION

Figures 2-5 show calculations of fission cross sections as described above and the data from this experiment. Also shown are comparisons to ^{4}He induced

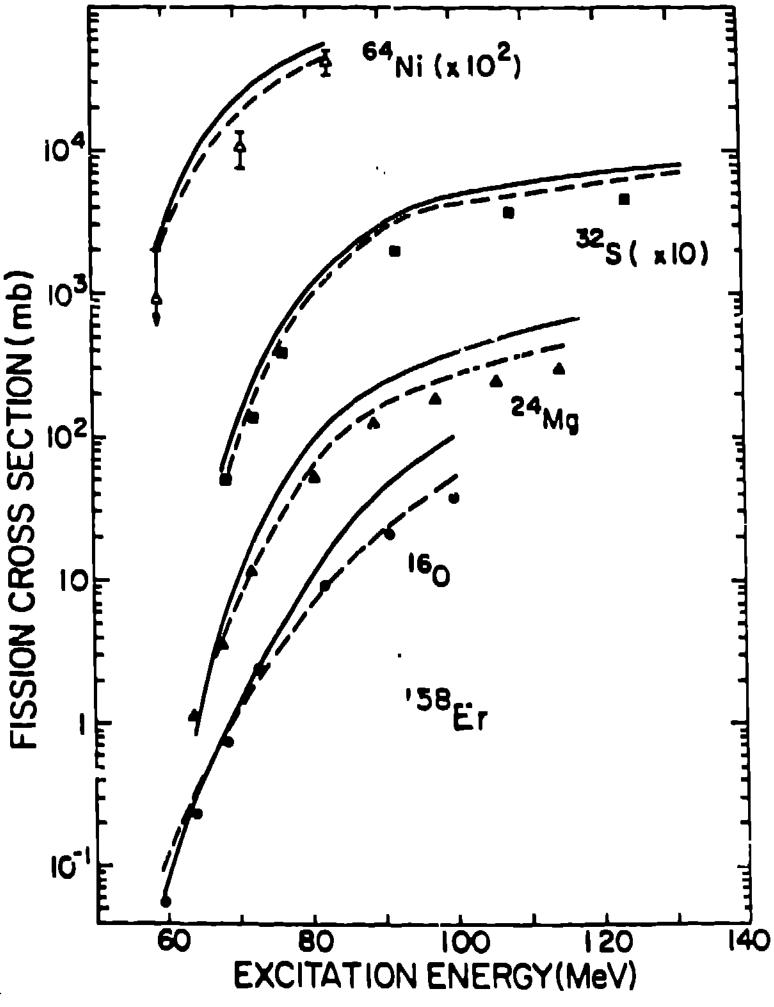

Fig. 2. Calculated fission cross sections compared to experimental data for the composite system ^{158}Er. Solid lines use Fermi gas based level densities and dashed lines use microscopic level densities (see text).

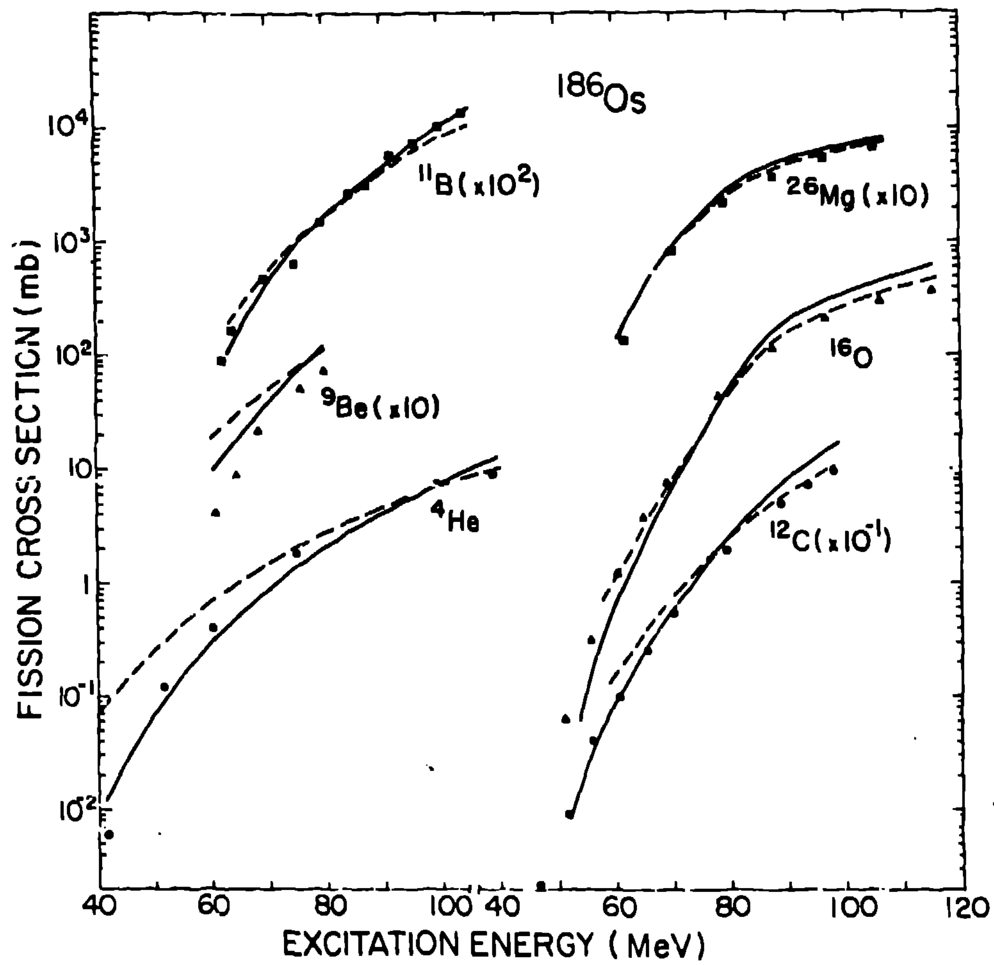

Fig. 3. Calculated fission cross sections compared to experimental data for the composite system ^{186}Os. Solid lines use Fermi gas based level densities and dashed lines use microscopic level densities (see text). Data for ^{4}He and ^{11}B reactions are taken from Refs. 21 and 3, respectively.

fission[21] for ^{186}Os and ^{210}Po, ^{11}B fission[3] for ^{186}Os and recent ^{19}F and ^{30}Si reactions[10] leading to ^{200}Pb. In this case the calculated evaporation residue cross sections agreed with their data to better than 10%.

With essentially no adjustable parameters the calculated cross sections agree remarkably well with experimental data over a very broad region. The success in describing data ranging from the rare earth region to the closed shell Pb-Po region and for bombarding particles ranging from ^{4}He to ^{32}S indicates that the overall excitation energy, angular momentum, and fissility dependences of the model must be reasonably correct.

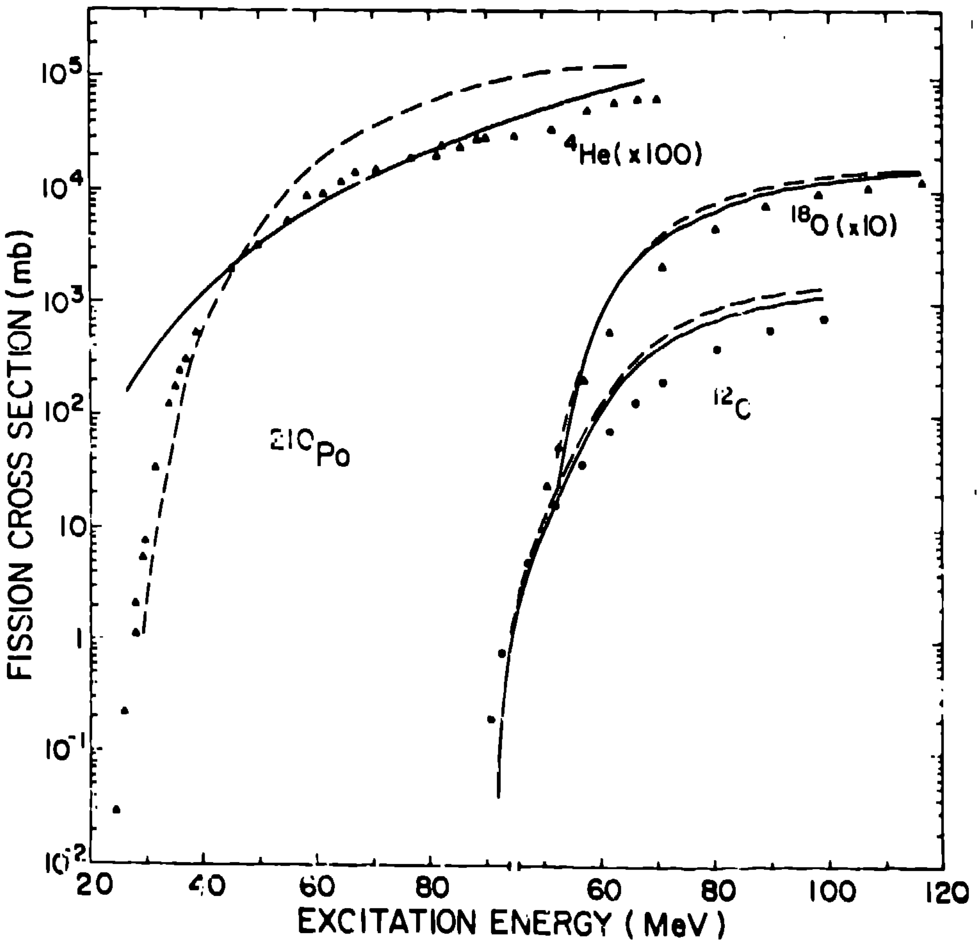

Fig. 4. Calculated fission cross sections compared to experimental data for the composite system ^{210}Po. Solid lines use Fermi gas based level densities and dashed lines use microscopic level densities (see text). Data for ^{4}He reaction are taken from Ref. 21.

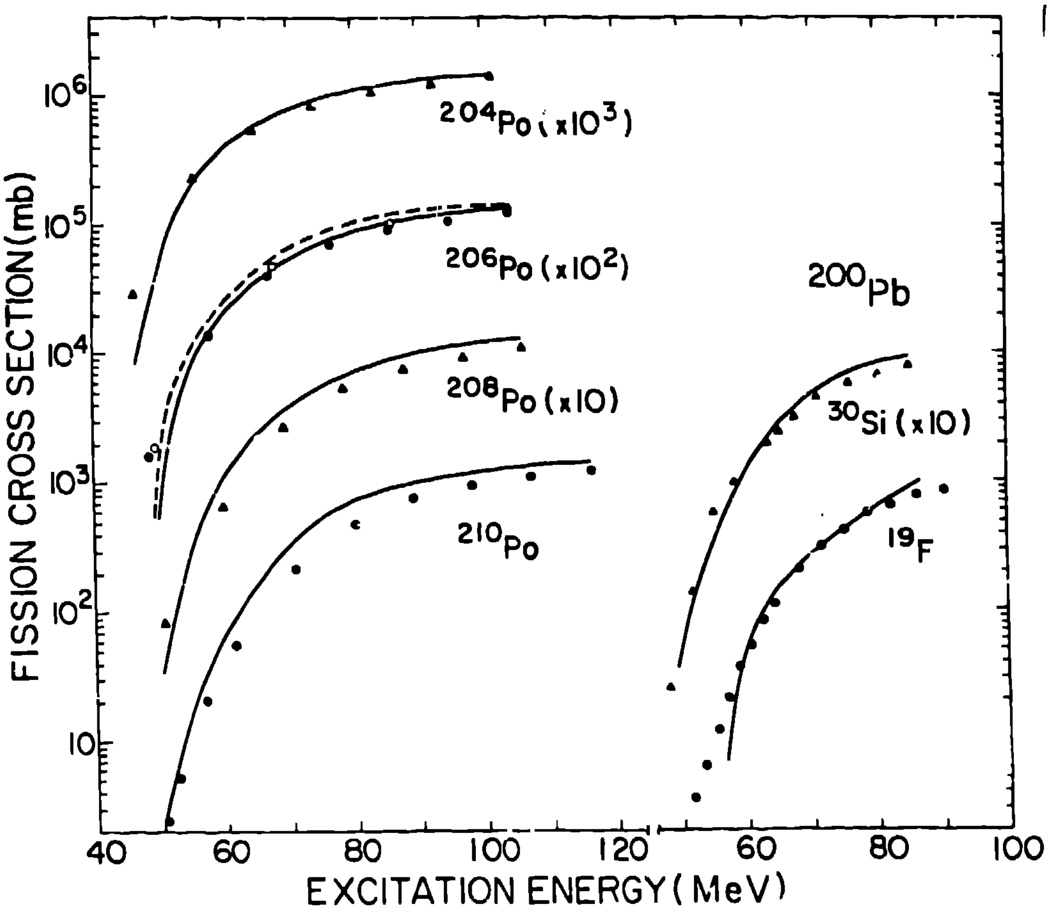

Fig. 5. Calculated fission cross sections compared to experimental data for Po isotopes and ^{200}Pb (Ref. 10). Calculations use Fermi gas based level densities. For ^{206}Po the solid curve, solid points are for the reaction with ^{16}O projectiles and dashed curve, open points are for ^{18}O projectiles.

In the case of the ^{4}He (and possibly ^{9}Be) induced reactions at the lower energies, the angular momenta brought in are well below the regions where the fission barrier has decreased to the order of the neutron binding energies. Thus, the fission cross section tends to be a sum over ℓ values for which each term has a small fission probability. In this case the data could test the fission barrier calculations at low angular momentum, but the calculations are also sensitive to the high energy behavior of the level densities, which may not be quantitatively understood.

For the higher energies and heavier projectiles a very different situation exists. Here the angular momentum distribution extends into the region of high fission probabilities. In these cases the fission cross sections are dominated by a sum of $\sigma(\ell)$ for angular momenta greater than the value for which $B_f = B_n$. If $B_f(\ell)$

is rapidly changing in this region then the level density functions are of less importance. In these cases the theoretical calculation is most sensitive to the calculated B_f in the angular momentum region where B_f crosses B_n and to the calculated fusion cross section.

Figure 6 shows a comparison of calculations using the barriers of CPS[11], Sierk[12] and Mustafa[17] compared with experimental data for two cases. We conclude that the Sierk barriers give the best overall representation of the experimental data.

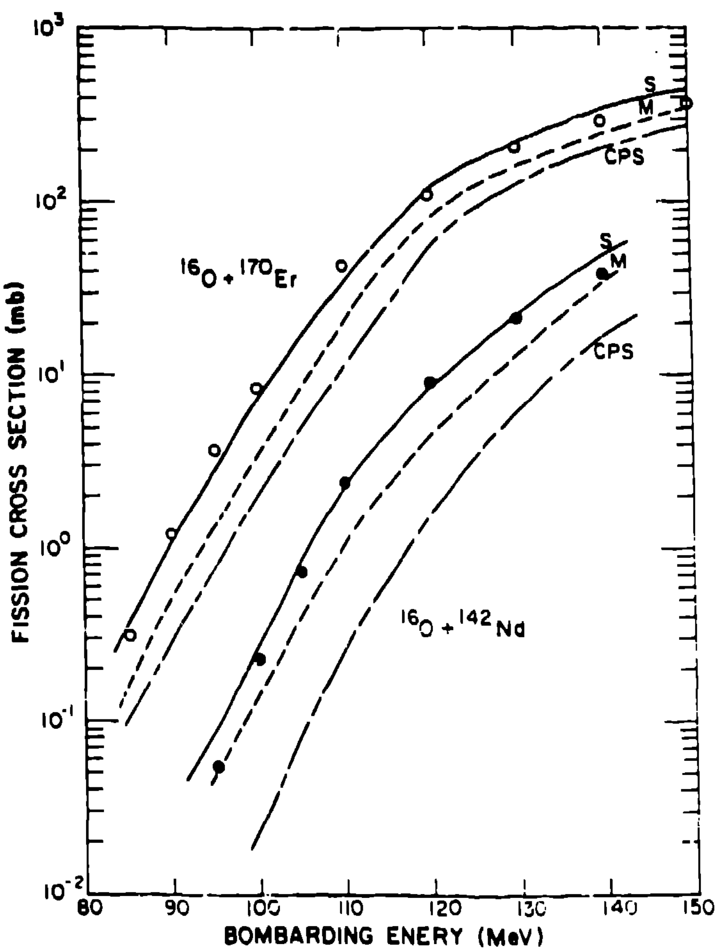

Fig. 6 Comparison of experimental data to calculations using the fission barriers calculated by Cohen, Plasil, and Swiatecki (Ref. 11), Sierk (Ref. 12) and Mustafa, Balsden and Chandra (Ref. 17).

The case of the reaction $^{64}Ni + ^{94}Zr \rightarrow ^{158}Er$ is qualitatively different from the other cases involving lighter projectiles. Here the reaction is dominated by quasi- and deep-inelastic reactions, but it was possible to isolate a symmetric fissionlike component. The increased uncertainty in isolating the symmetric fission component is reflected by the relatively large error bars shown in Fig. 2 for these cross sections. At the highest energies for the Ni and S induced reactions the angular momenta become large enough that "extra push" effects[22,23] could cause a decrease in the fusion cross section below the Bass model predictions. However, for our highest energy Ni reaction the model of Swiatecki[23] would predict only a 15-20% lowering of the fission cross section. An effect of this magnitude could not be significantly tested because of the other uncertainties of the same general magnitude which are present in the inputs to the theoretical statistical model.

SUMMARY

We have presented a comprehensive set of data on fission cross sections for Po, Os, and Er isotopes excited in a variety of heavy-ion reactions induced by projectiles from ^{9}Be through ^{64}Ni. The experimental results clearly show the qualitative effects of angular momentum, excitation energy and fissility on the fission cross section. They provide an ideal testing ground for theoretical models of fission in this mass region.

The results are compared to predictions from a theoretical model incorporating a new calculation of angular-momentum-dependent fission barriers by Sierk.[12] The predictions show remarkable agreement with experimental results without the need to involve arbitrary normalization factors on the calculated fission barrier function. Within the accuracy of the comparisons there is no need to invoke shell corrections at the saddle point. More quantitative tests of the calculated barriers would require experimental data on the evaporation residue cross sections, a knowledge of the properties of any incomplete fusion effects, and an improved model for the level densities used in estimating Γ_f/Γ_{total}.

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