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[14]G. Harp (private communication) has done an intranuclear cascade calculation of $\sigma^{\pm}$ and obtained somewhat poorer agreement with the data despite the strong similarity between the underlying assumptions of his work and ours.

[15]Although the physical basis of this model is very similar to the optical-model calculation of Hewson (Ref. 3), it differs in one rather important respect. Hewson used undistorted pion wave functions, i.e., he did not take into account the attenuation of the pion flux due to πN interactions. This results in a somewhat shorter path length for the nucleon than used here [Eq. (3)], which gives a smaller charge-exchange probability. Thus Hewson found values of $\mathcal{R}$ somewhat larger than the present experimental value at 180 MeV.

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Measurement and Interpretation of Γ_n/Γ_f for Actinide Nuclei*

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The (^{3}He, df) and (^{3}He,tf) reactions were used to measure fission probabilities from threshold up to ~12 MeV of excitation energy for a series of actinide nuclei. The data were fitted over the whole range of nuclei and excitation energies with a microscopic model which does not contain an arbitrary normalization for Γ_n/Γ_f. The fits indicate that for most actinide nuclei fission proceeds through a first saddle point that is *not* axially symmetric.

Previous experimental determinations[1] of Γ_n/Γ_f for actinide nuclei have primarily come from calculated total reaction cross sections or from the analysis of high-excitation–energy spallation cross sections. In the first case the results are limited both by the target nuclei available for study and by the accuracy of the calculated total reaction cross sections. In the second case the Γ_n/Γ_f values deduced represent an average over a range of excitation energies and decaying nuclei. In a few cases Γ_n/Γ_f values have been determined using (t,pf) reactions[2] but these measurements were only valid in the energy range up to 2 MeV above the neutron binding energy and they were limited to a relatively few nuclei.

Similarly the variations of Γ_n/Γ_f both with nucleus and with energy are only very schematically understood. Empirical trends with Z and A have been shown by Vandenbosch and Huizenga[1] but these trends or the energy dependence of Γ_n/Γ_f have not been reproduced in any theoretical calculations.

In this Letter we report three new developments which give significant improvements both to the techniques for measuring Γ_n/Γ_f and to a basic theoretical understanding of neutron-to-fission competition in actinide nuclei. These new developments are as follows: (1) The (^{3}He,df) and (^{3}He,tf) reactions are used to determine experimentally the absolute values of $P_f = \Gamma_f/(\Gamma_f + \Gamma_n + \Gamma_\gamma)$ for excitation energies up to ~12 MeV for a wide variety of nuclei which have not been previously accessible. (2) A theoretical calculation of P_f incorporating collective enhancements[3] to the nuclear level densities and a double-peaked fission barrier is shown to reproduce absolute values of

P_f over the entire range of actinide nuclei with no arbitrary normalization factor for the magnitude of Γ_n/Γ_f. (3) The fits to the absolute values of the fission probabilities with this new microscopic model require the assumption that at the first barrier most actinide nuclei do not possess axial symmetry.

The experimental procedures were similar to those reported previously[4,5] except that two fission detectors were used at angles ~0° and ~90° with respect to the kinematic recoil angle and the light-particle telescope was moved back to ~120° in order to minimize contributions to the singles spectra from reactions on ^{12}C and ^{16}O contaminants in the targets. This geometry allowed absolute fission-probability measurements up to an excitation energy of 11–12 MeV for (^{3}He,*df*) reactions with an incident ^{3}He energy of 25 MeV. As in previous experiments absolute values for the fission probabilities, P_f, are obtained from the ratio of coincidence and singles spectra. An improved particle identification system permitted a good separation of (^{3}He,*tf*) events though the cross section for the (^{3}He,*tf*) reaction was ~10 times less than that for the (^{3}He,*df*) reaction.

A composite presenting some of the experimentally measured fission-probability distributions is shown in Fig. 1. A serious concern in these experiments was whether the observed deuteron spectra would be contaminated with deuterons from the Coulomb breakup of the ^{3}He projectile and, thus, invalidate the direct measurement of P_f at high-excitation energies. Coulomb breakup is known to have a serious effect on (*d*,*pf*) results[5] but because of the difficulty in producing very low energy protons it seemed probable that the (^{3}He,*dp*) cross section would be very small in the energy range of interest in these experiments. To test this hypothesis several cases were studied where the same residual nuclei could be produced by both (^{3}He,*df*) and (^{3}He,*tf*) reactions. Results from two of these cases, ^{236}Np and ^{240}Am, are shown in Fig. 1, and it is seen that the agreement between results from the two reactions is reasonable and, in particular, the (^{3}He,*df*) results do not tend to show abnormally low P_f values at high E^* as would be the case if a significant Coulomb-breakup cross section were present. A study of the various possible systematic errors in these measurements indicates that in all cases the uncertainty in the absolute P_f values should be less than ±10%.

A composite of the Γ_n/Γ_f results determined at excitation energies of 8 and 11 MeV is shown in Fig. 2. Also shown are the empirical trends for other measurements of Γ_n/Γ_f in this region taken

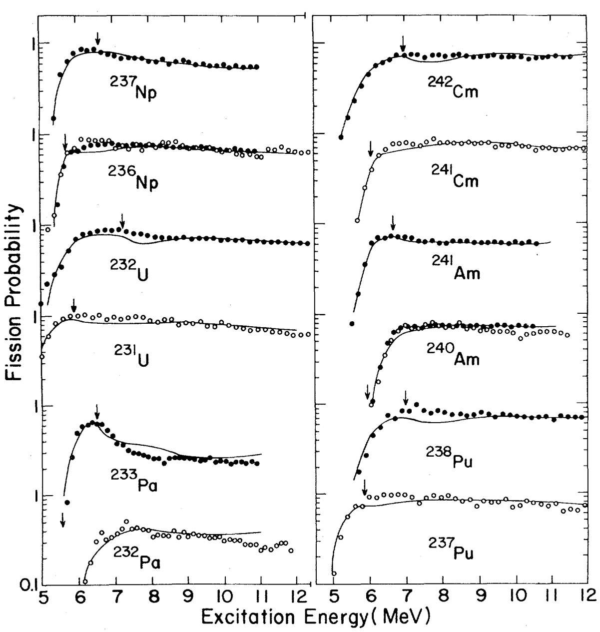

FIG. 1. Measured fission probabilities for a series of actinide nuclei. Solid points indicate results from (^{3}He,*df*) reactions. Open circles indicate results from (^{3}He,*tf*) reactions. Solid lines show fits with the microscopic statistical model described in the text. Arrows indicate positions of the neutron binding energy.

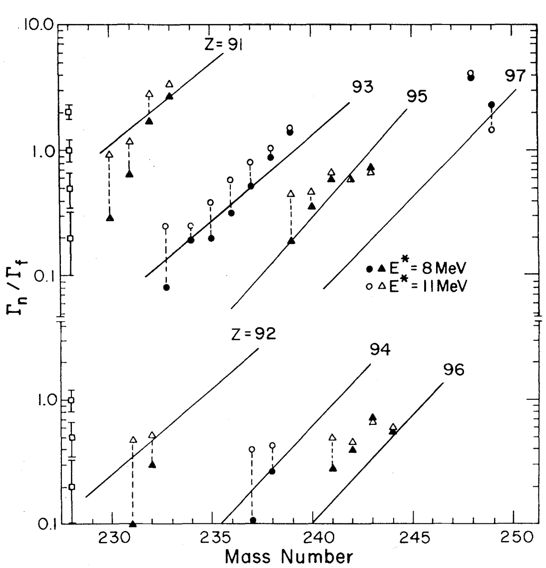

FIG. 2. Γ_n/Γ_f values deduced from measured fission probabilities at 8- and 11-MeV excitation energy. Solid lines show the "systematics" of Vandenbosch and Huizenga (Ref. 1). Open squares at left indicate the uncertainty in Γ_n/Γ_f resulting from a ±10% uncertainty in P_f.

from Vandenbosch and Huizenga.[1] The results are generally similar to the previous systematic values but now one can see significant energy variations for the lightest isotopes of most elements.

In an attempt to analyze these results we have modified the previous microscopic statistical model[5] used to fit P_f distributions in the threshold region. The major modification was to include the effects of collective enhancements[3] to the level densities. At the equilibrium deformation for the Γ_n calculation we assumed that the nucleus was statically deformed with axial and reflection symmetry so that the level density is given by[6]

$$\rho(E,I)=\frac{\omega(E)}{(8\pi)^{1/2}\sigma_{\parallel}}\sum_{K=-I}^{K=+I}\exp\left[-\frac{K^2}{2\sigma_{\parallel}^2}-\frac{I(I+1)-K^2}{2\sigma_{\perp}^2}\right], \qquad (1)$$

where $\omega(E)$ and $\sigma_{\parallel}(E)$ are taken from microscopic single-particle calculations[6,7] and $\sigma_{\perp}$ is an average experimental value ($\sigma_{\perp}=5.45$). In the Γ_f calculations the nucleus at the second saddle point was assumed to be reflection asymmetric but axially symmetric so that the level density was increased by a factor of 2 from the above expression. The appropriate symmetries at the first saddle point are not as clear since theoretical calculations[8,9] have shown a preference for axially asymmetric shapes in some cases and the possibility of reflection asymmetric shapes has not been investigated. Therefore, for level densities at the first saddle point, the model had the option of (1) axial and reflection symmetry, (2) D_2 symmetry (symmetry of rotation by 180° around three perpendicular axes), (3) only reflection symmetry or only 180° rotatational symmetry about one single axis, or (4) no symmetry. For the no-symmetry case the continuous level densities were approximated by

$$\rho(E,I)\simeq\omega(E)\sum_{I_3=-I}^{I_3=+I}\exp\left[-\frac{I_3^2}{2\sigma_{\perp}^2}-\frac{I(I+1)-I_3^2}{2\bar{\sigma}^2}\right], \qquad (2)$$

where I_3 is the projection on the 3 (z) axis, and $\bar{\sigma}^2$, approximated by $\sigma_{\parallel}^2$, from the microscopic level-density calculations, is an average spin factor for rotations about the other two axes. For the cases of interest the exponent factors are always near 1 so that accurate estimates for $\sigma_{\perp}$ or $\bar{\sigma}$ are not needed. For the case of reflection symmetry the level density in Eq. (2) is decreased by a factor of 2 whereas for D_2 symmetry it is decreased by a factor of 4. For axially asymmetric shapes $\omega(E)$ was calculated both at the first barrier and at the first minimum from single-particle levels for ^{240}Pu from Larsson and Leander.[10]

The fits with this statistical model to representative data from Pa through Cm are shown in Fig. 1. These fits all assume no symmetry at the first barrier.[11] In most cases the fits are sensitive to three parameters: the height and curvature of the inner barrier, E_A and $h\omega_A$, and the height of the outer barrier, E_B. The values obtained for these parameters agree within estimated errors with values obtained previously[4,5,7] from fitting P_f data near threshold and from the analysis of fission-isomar excitation functions. It is seen that with no adjustable normalization for Γ_n/Γ_f the model fits all of the data reasonably well both in the barrier region and at higher excitation energies. This is in contrast to previous fits[5] to threshold data which required a normalization of Γ_n/Γ_f which varied from 0.1 in heavy nuclei to ~1 for Th and Pa isotopes. Even with such a normalization the P_f distribution calculated with the previous model would often diverge sharply from the data for excitation energies above threshold.

For all of the nuclei the fits to absolute values of P_f require that the first barrier be assumed axially asymmetric.[12] Thus, within the framework of this model, the fits to these experimental data provide the first evidence that the nucleus actually proceeds toward fission through an axially asymmetric shape at the first barrier as predicted by many theoretical calculations.[8,9] These results compare to recent theoretical calculations[10] which indicate a potential energy gain associated with axially asymmetric shapes for $N \geq 142$. In addition, all of the fits in Fig. 1 assume that there are no reflection or 180° rotational symmetries at the first saddle point although in most cases reflection symmetry could be introduced and a reasonable fit still obtained. We can not at present rule out the possibility of systematic errors of the order of a factor of 2 in the level densities. Therefore, although we believe the results reasonably establish the existence of axially asymmetric shapes at the first barrier, we are not yet able to make a definitive statement regarding the question of reflection symmetry.

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[11]In fitting to the data we found that taking other sets of single-particle levels resulted in a variation of the appropriate decay widths by less than a factor of 2. This is because in the energy region of interest (below ~ 6 MeV) the shell and pairing effects tend to offset each other. In contrast, the enhancement of ~ 20 in the level densities due to axial asymmetry was crucial for obtaining absolute fits to the data. This enhancement at barrier A changed not only the overall normalization for Γ_f/Γ_n but also the energy dependence, because now for most cases barrier A determines the low-energy behavior while for energies of more than 2–3 MeV above threshold Γ_f/Γ_n is dominated by barrier B where $\rho(E)$ is rising more slowly.

[12]In cases where $E_A < E_B$ it is also possible to fit the experimental results with axially symmetric level densities but the values obtained for E_A are much lower then the values for neighboring nuclei. This possible ambiguity exists for ^{231}Pa, ^{233}Pa, ^{231}U, ^{232}U.

Evidence for the D State of ^{4}He

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From a study of experimental phase shifts for $p + {}^4$He elastic scattering at proton energies below 50 MeV we conclude that small D-state admixtures to the dominant S-state configuration exist in the ^{4}He ground state. This result is obtained by evaluating a forward dispersion relation for the $p + {}^4$He spin-flip scattering amplitude.

It has been recognized long ago that in the presence of noncentral forces the ground-state wave function of ^{4}He can be a mixture of $^1S_0$, $^3P_0$, and $^5D_0$ contributions.[1-4] Attempts to include tensor forces in calculations of the ^{4}He binding energy[1,2,4] have shown that a D-state admixture of 2–10% to the dominant S-state configuration can be expected to exist. P-state contributions should be much smaller, since they enter only in second order.[2-4]

To our knowledge, no experimental evidence for D-state contributions has ever been presented. Since ^{4}He has no spin, a D-state admixture does not give rise to a quadrupole moment. The only way to investigate such a configuration is to remove a nucleon from the ^{4}He ground state and to determine its orbital angular momentum. However, since the D-state contribution is small, its effects on any such process will be masked by those of the dominant S-state configuration, unless a process is studied to which the latter cannot contribute.

Such a selective process is the trinucleon exchange[5] in $N + {}^4$He spin-flip scattering as shown in Fig. 1. A nucleon spin-flip is only possible in this exchange scattering if the orbital angular momentum l at the vertices is not zero.[6] Since l is just the (asymptotic) orbital angular momentum of a nucleon in ^{4}He, the amplitude for this trinucleon exchange is proportional to ground-state admixtures with $l \neq 0$, or, neglecting P states, to