on ^{232}Th at energies of $(0.83-0.95)V_{CB}$ show predominantly two-proton and one-proton stripping, respectively, and the relative yields are in qualitative agreement with a simple calculation. Similar calculations for ^{86}Kr and ^{136}Xe projectiles suggest little transfer-induced fission because of the near-zero or negative Q-windows involved, while there is little probability of pure Coulomb fission with Kr particles. Yet the fission cross sections observed are similar for ^{16}O, ^{86}Kr, and ^{136}Xe. We would like to suggest that with the heavy ions, fission occurs as a result of the combination of Coulomb excitation and excitation from the tail of the Q window for particle transfer, the relative amounts changing toward more Coulomb excitation as one goes from light to heavy projectiles and to lower bombarding energy. For oxygen the process is primarily transfer induced; it would seem both processes are necessary with Kr, and the same is probably true with Xe. At least it seems difficult with Xe to speak of a pure Coulomb-induced or transfer-induced fission in the range $(0.85-1.0)V_{CB}$.

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[1]E. Guth and L. Wilets, Phys. Rev. Lett. 16, 30 (1966); L. Wilets, E. Guth, and J. S. Tenn. Phys. Rev. 156, 1349 (1967).

[2]K. Beyer and A. Winther, Phys. Lett. 30B, 296 (1969).

[3]H. Holm and W. Greiner, Nucl. Phys. A195, 333 (1972).

[4]V. Oberacker, G. Söff, and W. Greiner, J. Phys. C 3, L271 (1977).

[5]P. Colombani, P. A. Butler, I. Y. Lee, D. Cline, R. M. Diamond, F. S. Stephens, and D. Ward, Phys. Lett. 65B, 39 (1976); P. A. Butler, I. Y. Lee, J. O. Newton, Y. El-Masri, M. M. Alconard, P. Colombani, R. M. Diamond, F. S. Stephens, R. W. Lougheed, and E. K. Hulet, Phys. Lett. 68B, 122 (1977).

[6]D. Habs, V. Metag, J. Schukraft, H. J. Specht, C. O. Wene, and K. D. Hildenbrand, Z. Phys. A283, 261 (1977).

[7]R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic, New York, 1973).

[8]J. R. Leigh, R. M. Diamond, A. Johnston, J. O. Newton, and S. H. Sie, to be published.

[9]K. Alder, R. Morf, M. Pauli, and D. Trautmann, Nucl. Phys. A191, 399 (1972).

[10]P. J. A. Buttle and L. J. B. Goldfarb, Nucl. Phys. A176, 299 (1971).

[11]K. A. Erb, D. L. Hanson, R. J. Ascuitto, B. Sørensen, J. S. Vaagen, and J. J. Kolata, Phys. Rev. Lett. 33, 1102 (1974).

[12]G. Franz, W. Brüchle, H. Folger, B. Haefner, J. Klemm, J. V. Kratz, and W. Weber, Annual Report, Gesellschaft für Schwerionenforschung, Darmstadt 25, 1977 (unpublished).

Influence of Deformation upon Light-Particle Emission from High-Spin States in Nuclei

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We examine changes in light-particle emission from high-spin states in nuclei arising from a deformation dependence of the transmission coefficients. These changes are large enough to have measurable influences upon decay-product characteristics; consequently, the use in statistical models of transmission coefficients representative of spherical nuclei is probably inadequate.

Many investigations are in progress involving analyses of heavy-ion–reaction decay-product characteristics such as γ-ray multiplicities, particle multiplicities, total fusion cross sections, and the division of the fusion cross section between the formation of fission and evaporation-residue products (see, e.g., Hillis *et al.*,[1] Eyal *et al.*,[2] Gould *et al.*,[2] and Britt *et al.*[3]). The decay products of greatest current interest are those resulting from de-excitation from high-spin states. Nuclei at high angular momenta are predicted[4] to be highly deformed, and this has been incorporated in part into descriptions of the statistical rotating-liquid-drop model (see, e.g., Beckerman and co-workers[5-8]) of the decay process through the introduction of rotational energies of saddle-point and equilibrium deformed nuclei. While considerable attention[5-8] has been given to the resulting consequences regarding the decay into fission and evaporation-residue products, and the extraction of statistical fission parameters, it is important to recognize[7] that the large equilibrium deformations will influence the transmission coefficients for particle emission.

These transmission coefficients contain the dynamics of particle emission, and in this Letter we examine the influence of a deformation dependence of transmission coefficients upon particle emission. In particular, we consider the angular momenta and energy carried off by nucleons and α particles from high-spin states in ^{97}Rh and ^{149}Tb at an excitation energy of 90 MeV. The results should give an estimate as to how large deformation effects may be in a mass region where many experiments have been performed, while outlining how calculations might better be performed for any system.

One would expect two effects upon particle emission. The first would be a lowering of the Coulomb barrier for charged particles leaving the elongated nucleus; the second would be the occurrence of higher partial waves at each channel energy due to the larger radius, for emission along the prolate axis. This emission direction is the most probable one; thus to obtain estimates of the magnitude of these deformation effects we characterize all three particle degrees of freedom by that of emission along the prolate axis.

Our starting point was the rotating-liquid-drop[4] model which was used to estimate the prolate semimajor axis $R_{\max}$ of equilibrium deformed nuclei as a function of angular momentum. The ratio $f = R_{\max}/R_0$, where R_0 is the radius of the nonrotating spherical nucleus, was then used to scale the radius parameters of the global optical-model parameter sets employed previously.[6-8] Classical Coulomb barriers were calculated for a particle incident along the prolate axis. Direct integration over the volume of prolate spheroids was used for small deformations, and over a sum of spheres and spheroids, which approximate the rotating-liquid-drop shapes while conserving volume, for moderate to large deformations. From these integrations the ratios κ of classical Coulomb barriers of deformed to spherical nuclei were obtained. The nuclear charges used in the optical-model calculations were then replaced by effective charges which gave the same (reduced) Coulomb barriers at the new radii. Values of f and κ for the two nuclei considered in this work are summarized in columns 2 and 3 of Table I.

We next investigated the changes in statistical decay of nuclei at high angular momenta which result from substituting our deformation-dependent transmission coefficients for those assuming spherical nuclei. The calculations for the statistical rotating-liquid-drop model were performed using the code MB-II,[9] and the results are compared to those obtained previously[7] in Table I. Angular momenta of $40\hbar$ to $80\hbar$ were considered, spanning the transition from Hiskes to Beringer-Knox shapes[4]; the corresponding yrast energies are listed in column 4.

The average angular momentum removed from the excited nucleus by the emitted neutron may be seen to be a factor of 3 larger for ^{97}Rh at $70\hbar$ for the deformed versus the spherical nucleus, and a factor of 2 larger for ^{149}Tb at $80\hbar$. The net changes would be larger if multiple emission were considered. The average energy removed per neutron decreases with increasing angular momentum for the spherical case (temperatures decrease with increasing yrast energy) but remain nearly constant for the deformed case.

The results for α-particle emission are quali-

TABLE I. Angular momentum and energy removal.

Nuclide	I ($\hbar$)	f	κ	$E_{\min}(I)$ (MeV)	$\langle\Delta I_n\rangle$ ($\hbar$) a	$\langle\Delta I_n\rangle$ ($\hbar$) b	$\langle\epsilon_n\rangle$ (MeV) a	$\langle\epsilon_n\rangle$ (MeV) b	$\langle\Delta I_\alpha\rangle$ ($\hbar$) a	$\langle\Delta I_\alpha\rangle$ ($\hbar$) b	$\langle\epsilon_\alpha\rangle$ (MeV) a	$\langle\epsilon_\alpha\rangle$ (MeV) b
^{97}Rh	40	1.07	0.95	26	1.5	1.7	5.2	5.5	5.8	6.4	19.7	19.4
	50	1.10	0.92	38	1.8	2.2	5.0	5.3	7.8	8.8	20.7	20.5
	60	1.50	0.85	52	2.0	3.8	4.4	5.7	9.4	16.1	21.3	23.6
	70	1.80	0.80	64	1.5	4.6	3.3	5.3	10.0	21.8	20.5	24.9
^{149}Tb	60	1.10	0.92	28	1.4	1.7	4.1	4.4	5.8	6.7	22.1	21.2
	70	1.25	0.89	37	1.7	2.4	3.9	4.4	7.0	9.7	22.4	22.0
	80	1.55	0.82	46	1.5	3.2	3.5	4.4	7.4	15.1	22.2	23.1

[a] Spherical. [b] Deformed.

tatively similar to those for neutron emission. Note, however, that the average angular momentum removed by an α particle approaches $22\hbar$ for ^{97}Rh at $70\hbar$ and exceeds $15\hbar$ for ^{149}Tb at $80\hbar$. There are substantial increases in the probability of α-particle emission associated with the deformation effects, exceeding, for example, a factor of 1.6 for ^{97}Rh at $60\hbar$ and ^{149}Tb at $80\hbar$. While the average α-particle kinetic energies are predicted to remain fairly constant with increasing I for the spherical case, they are predicted to increase by 10 to 25% for the deformed case.

These results indicate that transmission coefficients used for treating the statistical decay of nuclei at high angular momenta cannot be evaluated by assuming spherical nuclei. There are many experimentally observable consequences of the above deformation effects. For a given statistical fission parameter set there will be increases in evaporation-residue survival of multiple-chance fission competition, because of the increased angular momentum removal as well as the increased number of channels available for evaporation. For many systems there may be substantial increases in α-particle emission from high-spin states resulting in shifts towards lower values in the mass and charge distributions of evaporation-residue products (perhaps of the type reported in Ref. 3). The increased angular-momentum removal will also be reflected in shifts towards lower values in the spin distributions in residual nuclei formed at the termination of particle emission. In addition, the deformation effects may lead to increased overlaps between the spin distributions of neighboring xn products. (However, it appears unlikely that this possibility can explain either the overlaps reported in Ref. 1 or the discrepancies in widths reported in Ref. 7.)

To summarize, we have investigated changes which occur in light-particle emission from high-spin states in nuclei, and which result from a deformation dependence of the transmission coefficients. These changes are large enough to have experimentally observable consequences; thus the use in statistical models of transmission coefficients characteristic of spherical nuclei is probably inadequate for the investigation of nuclear decay from high-spin states. A more detailed examination of the deformation effects probed in this work is clearly required.

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[1] D. L. Hillis, O. Christensen, B. Fernandez, A. J. Ferguson, J. D. Garrett, G. B.Hagemann, B. Herskind, B. B. Back, and F. Folkmann, Phys. Lett. 78B, 405 (1978).

[2] Y. Eyal, A. Gavron, I. Tserruya, Z. Fraenkel, Y. Eisin, S. Wald, R. Bass, G. R. Gould, G. Kreyling, R. Renfordt, K. Stelzer, R. Zitzmann, A. Gobbi, U. Lynen, H. Stelzer, I. Rode, and R. Bock, Phys. Rev. Lett. 41, 625 (1978); G. R. Gould, R. Bass, J. V. Czernecki, V. Hartmann, K. Stelzer, R. Zitzmann, and Y. Eyal, Z. Phys. A284, 353 (1978).

[3] H. C. Britt, B. H. Erkkila, P. D. Goldstone, R. H. Stokes, B. B. Back, F. Folkmann, O. Christensen, B. Fernandez, J. D. Garrett, G. B. Hagemann, B. Herskind, D. L. Hillis, F. Plasil, R. L. Ferguson, M. Blann, and H. H. Gutbrod, Phys. Rev. Lett. 39, 1458 (1977), and references therein.

[4] S. Cohen, F. Plasil, and W. J. Swiatecki, Ann. Phys. (N.Y.) 82, 557 (1974).

[5] M. Blann and F. Plasil, Phys. Rev. Lett. 29, 303 (1972); F. Plasil and M. Blann, Phys. Rev. C 11, 508 (1975).

[6] M. Beckerman and M. Blann, Phys. Rev. Lett. 38, 272 (1977), and Phys. Lett. 68B, 31 (1977).

[7] M. Beckerman and M. Blann, Phys. Rev. C 17, 1615 (1978).

[8] M. Beckerman, Phys. Lett. 78B, 17 (1978).

[9] M. Beckerman and M. Blann, University of Rochester Report No. UR-NSRL-135, 1977 (unpublished); MB-II description.