Nucl. Phys. 67, 1 (1965).
[3]J. Jänecke, Kernforschungszentrum Karlsruhe Report No. KFK-296, 1965 (unpublished).
[4]G. T. Garvey, J. Cerny, and R. H. Pehl, Phys. Rev. Letters 12, 726 (1964).
[5]E. Newman, J. C. Hiebert, and R. H. Bassel, Bull. Am. Phys. Soc. 10, 27 (1965); and to be published.
[6]L. C. Becker, J. C. Hiebert, and E. Newman, Phys. Rev. (to be published). R. H. Bassel, private communication.

PROPOSAL FOR AN EXPERIMENT ON ADIABATICALLY INDUCED COULOMB FISSION*

Eugene Guth
Oak Ridge National Laboratory, Oak Ridge, Tennessee

and

Lawrence Wilets
University of Washington, Seattle, Washington
(Received 18 October 1965)

Nuclear fission thresholds are fairly well known from the shape of cross-section curves as a function of energy. The thresholds yield directly the height of the saddle-point energy above the nuclear ground state. What is not so well known experimentally is the shape of the nucleus at the saddle point. Some information about this shape is known from (I) spontaneous fission lifetimes and the threshold behavior of the fission cross sections, and (II) the angular distribution of fission fragments. Both cases listed under (I) measure the quantity $\hbar\omega_f$, where $\omega_f = (C/B)^{1/2}$ is the inverted oscillator frequency at the top of the fission barrier. The position of the maximum does not enter. Both measurements yield[1] $\hbar\omega_f \approx 0.4$-$0.5$ MeV for even-even fissioners above the including uranium. Case (II) is model dependent and is based upon the variation in the statistical distribution of levels with deformation.[2] The purpose of this note is to propose an experiment which yields a measure of the saddle-point configuration in an easily interpretable manner.

To date, all induced (as distinct from spontaneous) fission experiments consist of depositing energy into a "compound nucleus," and then observing the decay through the fission channel. We propose introducing a Coulomb field which, ideally, distorts the "cold" nucleus up to a saddle point, after which the nucleus slides down the potential hill to scission. If the distorting potential is introduced sufficiently slowly, the interpretation of the experiments will involve only electrostatics and nuclear statics.

Consider a head-on collision between a projectile (1) and a target (2). Let the reduced mass and center-of-mass energy be denoted by mA_r and E. Then the classical turning point d (which we will choose to be outside the range of nuclear forces) is given by

$$E = Z_1 Z_2 e^2/d. \tag{1}$$

(This neglects the target distortion.) For present purposes, we calculate the electric polarization energy for a target assuming pure quadrupole distortion only; that is, the target contains only monopole and quadrupole moments. (The projectile is assumed to be unpolarized.) We will further consider only prolate, axially symmetric distortions, with the target axis perpendicular to the trajectory. (We ignore the tendency of the Coulomb field to introduce nonaxial symmetry or oblate deformation.[3]) The electric polarization energy is given by

$$V_Q = -\tfrac{1}{2} Z_1 e Q/d^3, \tag{2}$$

where Q is the expectation value of the operator qr^2P_2 for the target. If we further assume that the projectile moves very slowly (we present below calculations which do not make this assumption), then the condition for fission is that V_Q plus the target deformation energy $\epsilon(Q)$ have no maximum at closest approach. Since V_Q is linear in Q, it follows that the position of the inflection point in $V_Q + \epsilon$ is determined by ϵ. The threshold occurs for

$$\frac{Z_1 e}{2d^3} = \frac{d\epsilon}{dQ}\bigg|_{\text{inflection}} \equiv \epsilon' \tag{3}$$

or, taken together with (2), the "infinitely slow" threshold energy becomes

$$E_{\rm th}^{\infty}=[2Z_1^{\,2}Z_2^{\,3}e^5\epsilon']^{1/3}. \qquad (4)$$

Note that this requires no dynamical considerations, such as knowledge of the mass parameter B.

In order that the nucleus have sufficient time actually to distort during the encounter, the projectile must move slowly compared with the characteristic collective vibrational time. If this condition cannot be satisfied, fission can still be effected by going to higher energies (smaller impact parameter), but then nuclear dynamics must be considered, since the collective motion must acquire a finite momentum before the encounter ends.

The characteristic collision "frequency" at the turning point is

$$\omega_c^{\,2}=-\ddot{V}_Q/V_Q=3\ddot{d}/d=3Z_1Z_2e^2/mA_\gamma d^3. \qquad (5)$$

Substitution from (3) yields

$$\omega_c^{\,2}=6Z_2e\epsilon'/mA_\gamma. \qquad (6)$$

The "slowness" parameter is ω_c/ω_v, where ω_v is the characteristic β-vibrational frequency. (One might also consider using ω_c/ω_f.)

We have performed dynamical calculations to study the threshold energy for the fission of ${}_{92}U^{238}$ as a function of projectile mass. For this purpose we have introduced the following simplified model, which can be refined as experiment warrants.

All dynamics are treated classically, and the projectile motion $d(t)$ is calculated for a pure Coulomb force. A cubic form for $\epsilon(Q)$ is assumed, with the corresponding mass parameter equal to a constant. This makes $\omega_v=\omega_f$. If we make the identification

$$Q=(9/20\pi)^{1/2}Z_2eR_0^{\,2}\beta, \qquad (7)$$

then we can immediately express

$$\left(\frac{\omega_c}{\omega_v}\right)^2=\frac{6\epsilon_f(5\pi)^{1/2}}{mA_\gamma R_0^{\,2}\Delta\beta\omega_v^{\,2}}=\frac{116.8}{A_\gamma(\hbar\omega_v)^2}, \qquad (8)$$

where for the final numerical result we have used ϵ_f = height of fission barrier = 5.8 MeV, R_0 = 7 F, $\Delta\beta$ = distance from equilibrium to saddle = 1.

The results displayed in Fig. 1 assume[4] $\hbar\omega_v$ = 1 MeV. Since ω_c/ω_v is not small compared with unity, some impulse is transferred to the collective motion in order to carry the system over the barrier. This is measured by the "maximum-deformation kinetic energy." As long as this is not large compared with the pairing energy (~1 MeV), the process can be expected to be essentially adiabatic. The breakdown is expected to occur well above the pairing energy, but one interesting outcome of the experiments will be to observe how the breakdown occurs. Note that, particularly for heavy projectiles, the "closest approach," d, is fairly comfortably outside the range of nuclear forces.

These calculations are immediately reinterpretable for other values of $\hbar\omega_v$ while maintaining the remainder of the target parameters fixed. $E_{\rm th}/E_{\rm th}^{\infty}$ and the maximum-deformation kinetic energy are, in fact, only functions of $A_\gamma(\hbar\omega_v)^2$. For example, if you wish to consider $\hbar\omega_v$ = 0.75 MeV (a mean between the experimental values of $\hbar\omega_v$ and $\hbar\omega_f$), a projectile mass 100 would correspond to 48 in Fig. 1.

We wish to distinguish the process discussed here from usual Coulomb excitation.[5] The latter is usually described in terms of excitation of stationary states. The present process is not easily described in these terms, although it may be regarded as a (coherent) multiple excitation. We are most interested in not pro-

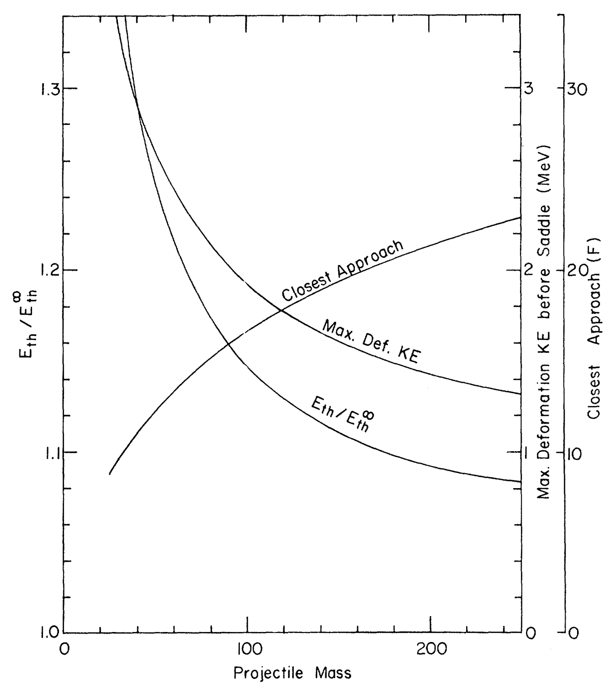

FIG. 1. Threshold energy for the fission of ${}_{92}U^{238}$ as a function of projectile mass.

ducing high excitations.

The magnitude of the cross sections anticipated is large. Detailed calculations are in progress, but we expect the differential fission cross section for scattering of the projectile into the backward direction to be the Coulomb differential cross section times a factor which involves the initial orientation of the target (and varies from 0 at threshold to perhaps the order of $\frac{1}{10}$ or 1/100). The Coulomb cross section is $(d/4)^2$. We are in the range ~1 mb/sr. (This assumes adiabaticity.)

Specifically, we propose experiments which involve (1) even-even targets such as Th^{232} and U^{238}; (2) the heaviest projectiles available at variable energies exceeding estimate (4); (3) coincidence of fission with the scattering of the projectile, particularly into the backward direction; (4) observation of the fission fragment angular distribution, which we expect to peak at 90° in the center-of-mass frame; (5) comparison of various fission characteristics, such as mass distribution, kinetic energy, etc., with other methods of inducing the reaction; and (6) measurement of projectile energy loss. Not all of these items are essential to a useful experiment.

We have learned[6] subsequent to the preparation of this note that an experiment on Coulomb fission (Ar^{40} on U^{238}) has been undertaken by T. Sikkeland at the Lawrence Radiation Laboratory, following a suggestion by A. Winther, who has considered some of these questions. Reference to Fig. 1 shows that a larger mass projectile would be desirable.

We wish to acknowledge stimulating discussions with Dr. J. J. Griffin, Dr. J. R. Huizenga, Dr. H. W. Schmitt, and Dr. P. H. Stelson.

---

*Work supported in part by the U. S. Atomic Energy Commission.

[1]J. R. Huizenga, private communication. See also I. Halpern, Ann. Rev. Nucl. Sci. 9, 245 (1959).

[2]This method was first used by R. Chaudhry, R. Vandenbosch, and J. R. Huizenga, Phys. Rev. 126, 220 (1962); cf. also "Deformation of the Transition State Nucleus in Energetic Fission," R. F. Reising, G. L. Bate, and J. R. Huizenga, Argonne National Laboratory (to be published).

[3]The fissile nuclei have static prolate deformations and are softer to further β deformation than to γ deformation. The stiffness to γ deformation undoubtedly increases as the nucleus deforms further. The shape that a nucleus assumes as it moves to fission would be that of a flattened cigar (γ small but not equal to zero). A quantitative statement of the flattening effect is model dependent, but we anticipate it to be small for the considerations here.

[4]E. K. Hyde, I. Perlman, and G. T. Seaborg, The Nuclear Properties of the Heavy Elements (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1964), Vol. I, p. 148.

[5]Cf. L. C. Biedenharn and P. J. Brussaard, Coulomb Excitation (Clarendon Press, Oxford, England, 1965). In an unpublished preprint, 1957, L. C. Biedenharn and R. M. Thaler specifically considered Coulomb excitation leading to fission.

[6]Private communications with T. Sikkeland and A. Winther.

HIGH-ORDER FLUCTUATIONS IN A SINGLE-MODE LASER FIELD*

F. T. Arecchi† and A. Berné‡

Laboratori Centro Informazioni Studi Esperienze, Milano, Italy

and

P. Bulamacchi

Centro Microonde, Firenze, Italy

(Received 29 November 1965)

There is a great deal of theoretical[1-4] and experimental[5-7] investigation about the statistical nature of a single-mode laser field, and the most-used model has been that of an amplitude-stabilized sine wave with a slowly varying random phase $E_0 \cos[\omega t + \varphi(t)]$ plus a stationary noise field $e_n(t)$ whose magnitude is much less than E_0. We give in this Letter experimental evidence of the accuracy of this model, pushing the field correlation measurements two orders further than the ordinary intensity fluctuations (or Hanbury Brown–Twiss type) experiments until now performed.[5-8]

First, we shall make some remarks on an experiment where we have superposed an amplitude-stable single-mode laser and a Gaussian field and studied the photon correlations in the superposed field. Then we shall apply