Note Added in Proof (Chapter 1)

A broad and genuinely live domain of nuclear heavy-ion science has been reviewed in the present chapter: since the submission of the manuscript for publication there have been reported plenty of new experimental and theoretical results substantially promoting the research field discussed. A few of these new findings were added to the text in the proofs; some others are highlighted below.

In early 1984, both at Dubna and Darmstadt, there were successfully completed experiments on the synthesis of element 108. The Dubna team, in studying products of the cold fusion reactions $^{209}Bi(^{55}Mn, n)$ and $^{207,208}Pb(^{58}Fe, 1\text{–}2n)$, has found that the element 108 isotopes with $A = 263\text{–}264$, including the even–even nucleus $^{264}108$, undergo mainly alpha decay (Og 84a, b); the partial spontaneous fission half life of $^{264}108$ has been estimated to be 0.1 ms or more (Og 84b). Somewhat earlier, when studying products of the $^{206,207,208}Pb(^{54}Cr, 1\text{–}2n)$ reactions, the dominance of alpha decay has been established at Dubna also for the element 106 isotopes of $A = 259\text{–}261$, with the following estimates for the partial spontaneous fission half lives (De 84b): $T_{sf}(^{259}106) \gtrsim 0.1$ s, $T_{sf}(^{260}106) \gtrsim 5$ ms, and $T_{sf}(^{261}106) \gtrsim 0.4$ s. At Darmstadt, Münzenberg *et al.* (Mü 84b), having detected three appropriate alpha decay chains, identified the isotope $^{265}108$ as an alpha emitter with $T_{1/2} = (1.8^{+2.2}_{-0.7})$ ms; this isotope has been produced in the $^{208}Pb(^{58}Fe, n)$ reaction with a cross section of (19^{+18}_{-11}) pb at a compound nucleus excitation energy of (18 ± 2) MeV. In a companion experiment, Münzenberg *et al.* have studied radioactive properties of the element of 106 isotopes with $A = 259\text{–}261$ formed in the $^{207,208}Pb(^{54}Cr, 1\text{–}2n)$ reactions and, in particular, they have found that the alpha-decaying isotope $^{260}106$ with $T_{1/2} = (3.6^{+1.1}_{-0.6})$ ms possesses a partial spontaneous fission half life of about 7–10 ms (Ar 84). The Dubna and Darmstadt data on the radioactive properties as well as production cross sections of the new nuclides are in reasonably good agreement.

The recent findings on the remarkable stability of the new even–even nuclei $^{260}106$ and $^{264}108$ with $x = 0.90\text{–}0.92$ as well as neighboring odd A nuclei essentially confirm the principal statements made in Section 2.1. All in all, the 25 transactinide species of $Z \gtrsim 104$ produced until now create a precedent for the existence of a large group of nuclei stabilized *solely* by the "shell" fission barrier and thus they manifest a straightforward evidence in favor of the existence of the near-magic superheavy nuclei with $Z \gtrsim 110$ and $N = 184$ that long ago have been predicted to be particularly stable against spontaneous fission.

We ought to state also that in the $^{208}Pb + ^{58}Fe$ system with $(Z^2/A)_{eff} = 38.0$ and $(Z^2/A)_m = 40.8$ the cold fusion still takes place so that the evaporation residue production cross sections, while being very low, of the order of 5–10 pb, are still quite detectable. Moreover, it is most probable that in the system $^{209}Bi + ^{58}Fe$ with $(Z^2/A)_{eff} = 38.3$ and $(Z^2/A)_m = 41.3$ the complete fusion also occurs resulting in the alpha-decaying nuclide $^{266}109$($x = 0.93$) with a production cross section of about 3 pb (Og 84b). The above conclusions seem to be potentially important to clarify the complete fusion issue for the heaviest reaction systems, which so far remains to be rather obscure even along qualitative lines. All the more, further experimental and theoretical work is of great urgency before any quantitative statements can be made regarding the change pattern of barriers and probabilities for the formation of a compound nucleus near the limits for fusion.

A progressive resurgence of interest to the angular distributions of fragments formed by heavy-ion induced fission stimulated production of new experimental data (Ga 84b, c, Tõ 84a, Va 84) as well as theoretical results (Bo 84d, Pl 84b, Pr 84, Ro 84, Tõ 84a) directed at clarifying the applicability limits of the standard statistical Halpern–Strutinsky theory of fission–fragment angular distributions or at expanding the theory towards high spins, high excitation energies, and large Z^2/A values. In particular, Gavron *et al.* (Ga 84b, c) have collected an extended data set on the fragment angular distributions for the following reactions: ^{12}C (at $E_{lab} =$ 95–291 MeV) on ^{174}Yb, ^{198}Pt, and ^{238}U; ^{16}O (at $E_{lab} = 140$–315 MeV) on ^{142}Nd, ^{170}Er, ^{192}Os, and ^{238}U. The measured angular distributions have been compared to those calculated within the standard statistical transition-state model assuming K distribution to be determined at the saddle point and using moments of inertia from saddle-point shapes with diffuse surfaces, provided by a rotating finite-range model of Sierk. Gavron *et al.* have found that the calculations agree with experimental angular distributions in those cases where, for a significant fraction of the partial waves contributing to fission, the fission barrier height $\tilde{B}_f(\bar{l})$ is comparable to or greater than the nuclear temperature at the saddle point, $T(\bar{l})$. When $\tilde{B}_f(\bar{l}) < T(\bar{l})$, the overall agreement with experiment is poor. In the cases where the model disagrees with experiment, the measured anisotropies, as a rule, substantially exceed the calculated ones. Therefore Gavron *et al.* (Ga 84b) assume that, when $\tilde{B}_f(\bar{l}) < T(\bar{l})$, either the shapes controlling angular anisotropy are more extended than the saddle-point shapes or the passing to the scission configuration is too rapid to enable the K quantum number to be completely equilibrated so that the effective K distribution will be narrower than the predicted one and the angular distribution will be more anisotropic; in such cases the K distribution seems to be governed by the reaction dynamics. Then the degree of the discrepancy between calculations and measurements could be considered (Ga 84b) as a manifestation of the time scale involved: the lighter the projectile and the lower the bombarding energy, the longer the time scale and, consequently, the smaller the discrepancy between the calculated and measured anisotropies.

In order to describe the fission–fragment angular distributions in the cases of $\tilde{B}_f(\bar{l}) < T(\bar{l})$, when a transition state (or saddle point) in fission is absent, Rossner *et al.* (Ro 84) have applied a phenomenological statistical scission model of angular distributions, first suggested by Ericson (Er 60), in which the fate of the fission process is determined by the phase space available at the scission point. The essence of the model consists in assuming a statistical partition of the initial angular momentum $\mathbf{l}$ of the fissioning nucleus into orbital angular momentum $\mathbf{I}$ and channel spin $\mathbf{S}$ of the two primary fission fragments, where $\mathbf{l} = \mathbf{I} + \mathbf{S}$. It is these quantities which control the fragment angular distribution. Comparison of the Rossner *et al.* model calculations to experimental data has demonstrated (Ro 84) a good agreement for the systems ^{40}Ar ($E_{\text{lab}} = 340$ MeV) on ^{238}U (Le 83b) and ^{32}S ($E_{\text{lab}} = 266$ MeV) on ^{208}Pb (Ba 83a, b) as well as for many other systems in a wide range of fissility parameter, excitation energy, and spin value.

Thus, even though a great deal of details concerning fragment angular distributions is still to be clarified, nevertheless, one can state that the standard transition-state model of angular distributions works when it is expected to, viz., when $\tilde{B}_f(\bar{l}) > T(\bar{l})$; just as the rotating liquid drop model —with due regard for its generalized versions (Mu 82d, Ga 84b) and within the limits of its applicability (Co 74, Pl 84b)—provides a fairly good representation of x and l dependences of the saddle-point shapes. Following Plasil (Pl 84b), we shall, however, stress that the saddle-point shapes predicted by the rotating liquid drop model for $l = l_{B_f}$ are never spherical (except for the extreme $x = 1$, where $\tilde{B}_f = 0$ at $l = 0$) and thus $K_0^2 \neq \infty$ at $l > l_{B_f}$; therefore, using $K_0^2 = \infty$ for $l > l_{B_f}$ [explicitly or implicitly made in a number of works (Ba 83a, b, Bo 84d, Le 83b, Ro 83a, Ts 83a)] can lead to incorrect conclusions, and effects of the error are expected to be the greater the smaller value of x. On the other hand, for very heavy systems, i.e., for high x values, the saddle-point shapes from the rotating liquid drop model are compact and triaxial, and the axial approximation is known not to be adequate (Co 74). For triaxial nuclei, K_0^2 and J_{eff} are not defined and theoretical expressions for angular distributions should be modified to take this into account. Again, the rotating liquid drop model (Co 74) predicts that no saddle-point shapes exist for $l > l_{B_f}$. Consequently, the standard theory of angular distributions suggesting the presence of a saddle point should not be used in conjunction with the rotating liquid drop model values of K_0^2 and J_{eff} extrapolated for $l > l_{B_f}$. On balance, concludes Plasil (Pl 84b), the data on the reactions involving angular moments beyond the $l = l_{B_f}$ limit (Ba 83a, b, Le 83b, Ro 83a, Ts 83a) should not be used as a basis to make any claim regarding the validity of the rotating liquid drop model (Co 74) and statements concerning the value of K_0^2 in such cases should be based on considerations other than those of the rotating liquid drop model.

As to the l-dependent fission barriers, we note here three new statistical-model analyses of experimental data on high-spin fission of compound nuclei with $A \simeq 150-200$ (De 84a, Ka 84, Pl 84a). For the rare-earth domain, by studying the compound nuclei ^{153}Tb and ^{181}Re, Plasil *et al.* (Pl 84a) have found that, firstly, the rotating finite range model by Sierk (unpublished) or that by Mustafa *et al.* (Mu 82d), in which effects of the finite range of the nuclear force and of the diffuseness of the nuclear surface are included, adequately reproduce the experimental fission cross sections without any renormalization and, secondly, the new fission barriers calculated by Sierk and by Mustafa *et al.* are valid at least in the mass region from 150 to 210, [see also the papers (Br 83b, Pl 83)]. Delagrange *et al.* (De 84a) as well as Karwowski and Vigdor (Ka 84) state, in turn, that a satisfactory description of experimental fissionability data for high-spin compound nuclei of $A \simeq 200$ is obtained with the fission barriers from the rotating liquid drop model by Cohen *et al.* (Co 74) and no lowering of the barriers is required here. In these two analyses the agreement between statistical-model calculations and experiment without the need to modify the barriers is achieved owing to employment of specifically improved level density treatments; however, the level density philosophy of Delagrange *et al.* (De 84a) differs remarkably from that of Karwowski and Vigdor (Ka 84).

Recently there has been obtained a considerable body of experimental evidence indicative of multifold particle emission from a compound or mononucleus prior to the onset of fission competition [see, e.g., the papers (Al 82, Br 82b, Ki 82, Mi 78, Ra 82a, Ri 82a, b, Va 84, We 84b) and references therein]. Such effects are largely observed for very fissile, highly excited and/or rapidly rotating nuclear systems with a vanishing fission barrier, $\tilde{B}_f(\bar{l}) \lesssim T(\bar{l})$, and the standard statistical transition-state model fails to describe them, just as it fails to represent fission–fragment angular distributions in these cases. Further development of alternative theoretical formulations of the fission process, in particular, exploration of the diffusion approach, is the subject of the recent papers (Ha 84b, Mo 82, Ni 84a, b, We 84a, b) containing, among other items, attempts to explain and evaluate the effects of the delayed onset of fission competition to particle evaporation. Let us incidentally note that in analyzing the data which signal an unexpectedly high yield of prefission neutrons, especially those for heaviest fissioning systems, one must account for neutron evaporation during the acceleration of fission fragments up to their asymptotic velocity (Ei 65): when studying fission of ^{251}Es formed in the reaction $^{232}\mathrm{Th} + {}^{19}\mathrm{F}$ ($E_{\mathrm{lab}} = 124$ MeV), Hinde *et al.* (Hi 84) have experimentally demonstrated that this contribution can be very large—it comprises about three neutrons in this particular case.

New interesting experimental information has also been gained concerning the fast fission process and extra-push-type effects, which are expected to occur in the domain of high angular momenta, excitation energies, and Z^2/A values (Ga 84c, Gu 84, Le 84, To 84a,b, Zh 84). In particular, by measuring the energy dependence of symmetric fragmentation cross sections and of fragment mass and energy distributions for the systems ^{40}Ar ($E_{\text{lab}} = 210$–300 MeV) on ^{197}Ar, ^{209}Bi, and ^{238}U (Zh 84) as well as ^{35}Cl ($E_{\text{lab}} = 240$–350 MeV) on ^{238}U (Le 84), further experimental evidence has been obtained in favor of a fast fission process interpreted as "fission without barrier". An interesting feature of the new data consists in the following fact: while in the systems ^{40}Ar + ^{197}Au and ^{40}Ar + ^{209}Bi the mass distribution variance σ_A^2 strongly increases with bombarding energy, in the ^{40}Ar + ^{238}U and ^{35}Cl + ^{238}U systems it remains essentially constant at a very large value, $\sigma_A^2 \approx 1000$ (amu)^2. Various qualitative explanations of this fact —all being consistent with the fast fission hypothesis—have been proposed by the authors of the experiments (Le 84, Zh 84).

In clarifying properties of fast fission and conditions for its setting in, of importance is experimental information on the angular-momentum dependence of the mass and kinetic energy distribution variances for fission fragments of a *genuine* compound nucleus. A valuable set of such data was obtained by Glagola *et al.* (Gl 84) for the fissioning systems produced in the fusion reactions ^{16}O ($E_{\text{lab}} = 90$–148 MeV) on ^{170}Yb and ^{32}S ($E_{\text{lab}} = 180$–230 MeV) on ^{144,150,152,154}Sm. For the compound nucleus ^{186}Pt, in the excitation energy range of 60–100 MeV, the measured σ_A^2 values prove to be by some 20% larger when the compound nucleus is formed by the ^{32}S ions which obviously generate higher average angular momenta $\bar{l}$ than the ^{16}O ions do (for the given excitation energy range, $\bar{l}$ was estimated to be 32–54 $\hbar$ in the ^{32}S case and 30–45 $\hbar$ in the ^{16}O case); the angular-momentum induced increment in the total kinetic energy variance is smaller and amounts to about 5–10%.

Guarino *et al.* (Gu 84) have experimentally studied a mass drift between a heavy and a light nucleus in the reactions ^{238}U + ^{48}Ca, ^{238}U + ^{50}Ti, and ^{208}Pb + ^{56}Fe at bombarding energies of the ^{238}U and ^{208}Pb projectiles ranging between 4.6 and 6.1 MeV/nucleon. The mass drift was observed as a function of total kinetic energy and scattering angle of primary reaction products. Particularly striking has been the observation of a very large mass transfer towards symmetry already at lowest bombarding energies in the vicinity of the reaction barrier; this mass drift towards symmetry could favor fast fission without compound nucleus formation.

An extended set of new experimental data on reactions between ^{238}U ions of 5.4 and 6.0 MeV/nucleon and target nuclei ^{16}O, ^{27}Al, ^{48}Ca, ^{45}Sc,

^{48}Ti, ^{58}Fe, ^{64}Ni, and ^{89}Y has been reported recently by Tõke *et al.* (To 84b). Here accurate triple-differential cross sections, $d^3\sigma/dA \cdot d\Theta_{cm} \cdot dTKE$, are obtained for the binary events within the full range of mass A and total kinetic energy TKE, and within almost full range of center-of-mass angle Θ_{cm}. Apart from the reaction on ^{16}O, all the capture product distributions are found to be dominated by the fast fission process. With the ^{27}Al target the evolution of the reaction complex towards mass symmetry is almost complete whereas the heavier systems show very broad mass distributions with clear evidence of reseparation occurring before mass symmetry is reached. At the same time, the fast fission cross section diminishes as the target Z value increases, and for the ^{89}Y target the deep inelastic scattering component completely dominates. The capture cross sections for the ^{238}U-induced reactions are found to be well described by the extra-push model (Sw 81a, b, Sw 82, Bj 82c), however, a comparison of the present results to those obtained previously (Bo 82a) with a ^{208}Pb beam and similar targets shows that the scaling in the entrance-channel fissility x_{eff} is only an approximate law; the double magicity of ^{208}Pb is pointed out (To 84b) as offering an interesting clue to understand the differences in the magnitudes of the extra push needed to achieve capture in the ^{238}U and ^{208}Pb-induced reactions. From the measured angular distributions the characteristic $1/e$ relaxation time for the mass asymmetry motion is found to be equal to $(5.2 \pm 0.5) \times 10^{-21}$ s. As a whole, the Tõke *et al.* (To 84b) studies provide a deep insight into the fast fission process thought of as the mass drift mode in heavy-ion reactions. Furthermore, they rise the question (To 84b) as to why there are two separate channels in heavy-ion reactions—deep inelastic collisions and fast fission, and why are the two channels so pure? An unambiguous answer to this question would be of fundamental importance to understand the essence of highly inelastic nucleus–nucleus collisions.

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