PROMPT GAMMA DECAY OF FISSION FRAGMENTS

R. SARKAR
Saha Institute of Nuclear Physics, Calcutta - 9, India

and

A. CHATTERJEE
Calcutta University and Saha Institute of Nuclear Physics, Calcutta - 9, India

Recieved 8 September 1970

Prompt γ-ray energies and yields from fission fragments for the thermal neutron fission of ^{235}U and spontaneous fission of ^{252}Cf are calculated from an improved renormalised Fermi gas model and the collective potential energy surface concept. The predictions agree fairly well with the experimental observations.

An attempt was made [1,2] to treat the fission energy kinetics at the scissionpoint in a self-consistent way without the help of a conventional mass formula by combining two microscopic models of nuclear structure: (a) the collective potential energy surface concept of Mosel and Greiner [3] and (b) the interacting renormalised Fermi gas model developed by us [1,2]. The proving grounds of the ideas were the thermal neutron induced fission of ^{233}U and spontaneous fission of ^{252}Cf [1], the thermal neutron fission of ^{235}U and ^{239}Pu [2] and the fast neutron fission of ^{238}U [4]. Fair agreement was found in all cases with the mass-formula estimates of the total energy release E_R, the observed fragment excitation energy U_F and the measured fragment kinetic energy T_F. The overall agreement was found to be better than previous attempts based on the statistical model [5], the liquid drop model [6] and with shell corrections on the liquid drop model [7, 8]. In the work of Dickmann and Dietrich [7], the shell and BCS parameters are essentially the same as ours. They also used two liquid drop model parameters, the surface tension τ and the Strutinskii-type shell-width γ; we have used the Mosel-Greiner collective coefficients C_0 and C' instead. However, the agreement in the fragment excitation energies with observations for ^{235}U + n fission is found to be much better in our case [7, fig. 5; 2, fig. 2]. Similar comments and conclusions apply to the work of Schmitt [8].

After a brief summary of our previous procedure [1,2], we suggest a few improvements in our treatment of the stiffness coefficients C_0 and C'. The contribution of the reciprocal monopole-quadrupole Coulomb interaction to the prompt γ-decay processes in the fragments is discussed. Considerations of the fragment deexcitation lead process and the nature of nuclear levels in cascade E2 transitions lead to the correct evaluation of the γ-ray energy available in, and the mean number of γ-rays emitted from, each fragment.

We briefly recount our approach in [1] and [2]. The total intrinsic energy (BCS plus Coulomb energies) of a fissioning nucleus A consisting of Z protons and N neutrons

$$E_A(\alpha) = \sum_{Z,N} \Big(\sum_i e_i v_i^2 + \Delta^2/G\Big) + E_{C_A}(\alpha) \qquad (1)$$

is minimised with respect to the shape deformation α at the saddlescission point. The nuclear part in (1) is composed of (i) a static structural part at the ground state deformation β, evaluated from the renormalised Fermi gas model and (ii) a shape-dependent part estimated from the axially symmetric potential energy surface expansion in a power series in the shape deviation upto $(\alpha-\beta)^3$ with appropriate stiffness coefficients C_0 and C'; the Coulomb energy $E_{C_A}(\alpha)$ is given a similar well-known expansion upto $(\alpha^3-\beta^3)$. The intrinsic energy changes of the fissioning nucleus I were balanced with those of the mutually interacting prompt fission fragments (L and H) at the saddle-scission point:

$$E_{\mathrm{I}}(\alpha_{\mathrm{I}}) = \sum_{\mathrm{F=L,H}} \{E_{\mathrm{F}}(\beta_{\mathrm{F}}) + \tfrac{1}{2} C_{0_{\mathrm{F}}} (\alpha_{\mathrm{F}} - \beta_{\mathrm{F}})^2 + \tag{2}$$

$$+ C'_{\mathrm{F}} (\alpha_{\mathrm{F}} - \beta_{\mathrm{F}})^3 + E_{C_{\mathrm{F}}}(\alpha_{\mathrm{F}}) - E_{C_{\mathrm{F}}}(\beta_{\mathrm{F}})\} + E_{\mathrm{r}} - E_{\mathrm{d}} + E_{\mathrm{q}}$$

The interaction terms E_{r}, E_{d} and E_{q} have been discussed and deduced by Wilets [9] for terms linear in α [1, eq. (5); 2, eq. (13)]. The Wilets terms E_{r} and E_{d} were assumed in refs. [1,2] to go into the translational energy of the fragments T_{F}; the interaction energy E_{q} was predicted [1,2] to give rise to E2 type prompt γ-rays at the final stages of the gragment deexcitation process.

Our previous treatment [1,2] assumed all nuclei to have the same average stiffness coefficients $C_{0_{\mathrm{F}}}$ and C'_{F} in eq. (2). One would expect, however, the nuclear structure effects to show up in $C_{0_{\mathrm{F}}}$ and C'_{F}. A more detailed interconnection between the renormalised Fermi gas model and potential energy surface is obtained by assuming them to be functions of extracore nucleons n in a nucleus $A_{\mathrm{F}}(n/A_{\mathrm{F}} \equiv \delta\epsilon_{\mathrm{F}}/\epsilon_0)$. The occupation dependence of the coefficients are assumed here to be of the form

$$C_{0_{\mathrm{F}}} = C_{00}(1 - \delta\epsilon_{\mathrm{F}}/\epsilon_0), \quad C'_{\mathrm{F}} = C'_0(1 - \delta\epsilon_{\mathrm{F}}/\epsilon_0) \tag{3}$$

where C_{00} and C'_0 are the stiffness coefficients of a free Fermi gas (renormalised Fermi gas model correction $\delta\epsilon_{\mathrm{F}} = 0$). We have chosen $C_{00} = 320$ MeV and $C'_0 = 160$ MeV through trial and error for better energy fits of eq. (2) with observations. This small improvement (3) does not change the qualitative behaviour in the published energy curves in refs. [1] and [2] and in fact gives better shape fits in some mass regions. These chosen values of C_{00} and C'_0 agree with the average values of Mosel and Greiner [3]. It is possible to deduce a value of $C_{00} \approx 350$ MeV from elementary considerations of the renormalised Fermi gas model [10].

The fission energy release E_{R} and the components of internal energy (E_{R}, E_{d}, E_{q} and the Coulomb energy difference) of the prompt fragment F have been recalculated by minimising the total energy at the saddle-scission point as before [1,2]. The fission barrier for ^{235}U + n is correctly reproduced (5.64 MeV; experimental value is 5.75 MeV; our previous value without using eq. (3) was 4.4 MeV). The fragment deformations are now more strongly fluctuating than in refs. [1,2] due to the relative structural differences of the fragment nucleides. These calculated deformations are shown at the top sections marked (a) in figs. 1 and 2 for the thermal neutron induced fission of ^{235}U and spontaneous fission of ^{252}Cf respectively. There are no liquid drop model calculations for the fragment deformations α_{F} for ^{252}Cf, but Ferguson and Read [6] have estimated α_{F} for a few fragment pairs for the ^{235}U + n fission from the liquid drop model;

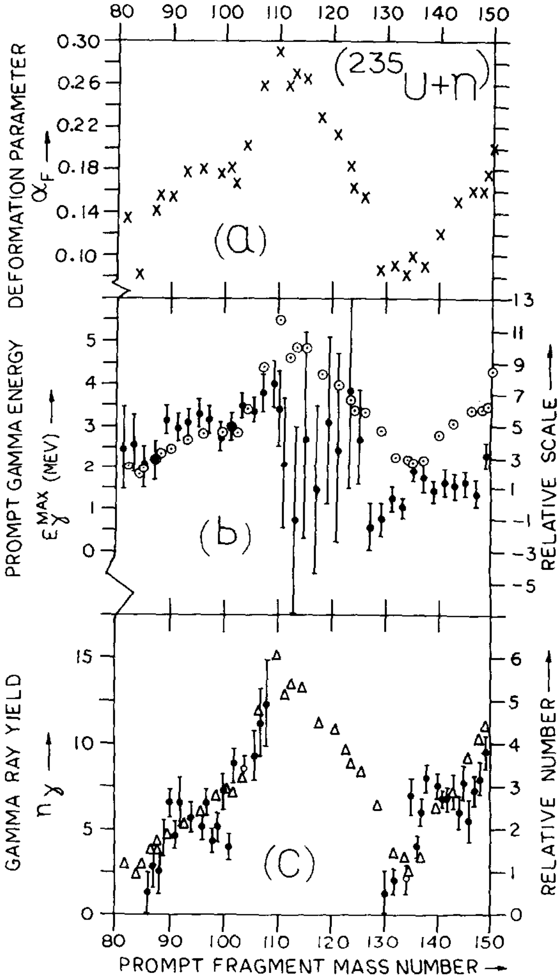

Fig. 1. Calculated quantities α_{F}, E_γ^{max} and n_γ for the ^{235}U + fission reaction with thermal neutrons, plotted against the prompt fragment mass number A_{F}. 1(a): The scission point deformation parameter α_{F} estimated from eq. (2); 1(b): The available γ-decay energy E_γ^{max} calculated by solving eq. (2) are shown as ⊙ and are compared with the data (⧱) of ref. [15]; the calculated energies are slightly lower for heavy fragments and higher for light ones; 1(c): The mean photon number n_γ shown as Δ are compared with the data of ref. [15].

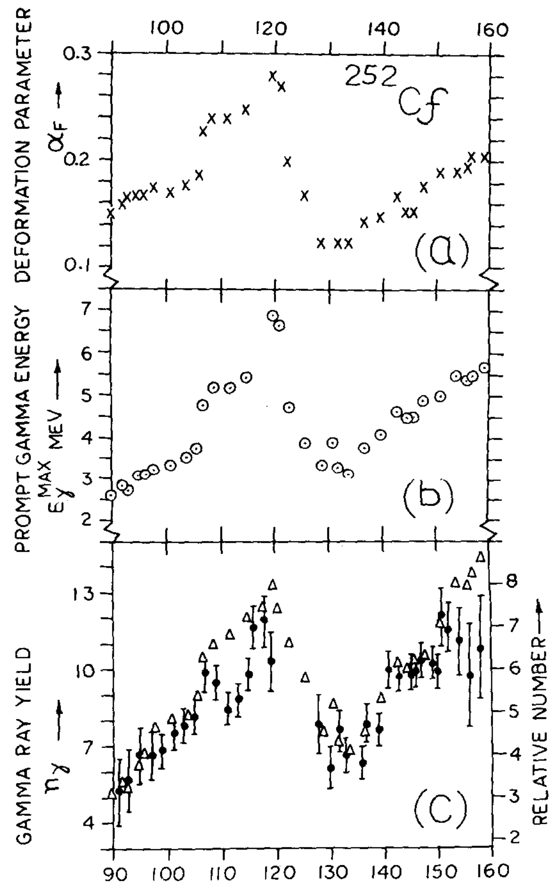

Fig. 2. Calculations of α_F, E_γ^{max} and n_γ for the spontaneous fission of ^{252}Cf. For details (a), (b) and (c), see the respective captions of fig. 1. No experimental comparison is possible in fig. 2(b). The experimental data of fig. 2(c) are from ref. [14]. The relative scales of the quantities on the right in both figs. 1 and 2 are those used by the experimentors [14, 15].

their estimates for α_F are in fair agreement with our calculations.

The quadrupole-monopole interaction energy between the fragment pairs E_q is identified as the γ-emission energy E_γ^{max}. The physical situation here is that a free vibrating quadrupole q is held in constraint by a charge monopole at a finite distance $r = R_{0_L} + R_{0_H}$ and hence the potential energy of the quadrupole increases [11]; removal of the interaction allowes the stored potential energy of the quadrupole to be released. Since the postscission configuration of the recoiling fragments may be taken as the snapping process of this interaction, the extra stored energies in the quadrupoles E_{q_L} and E_{q_H} left to themselves,

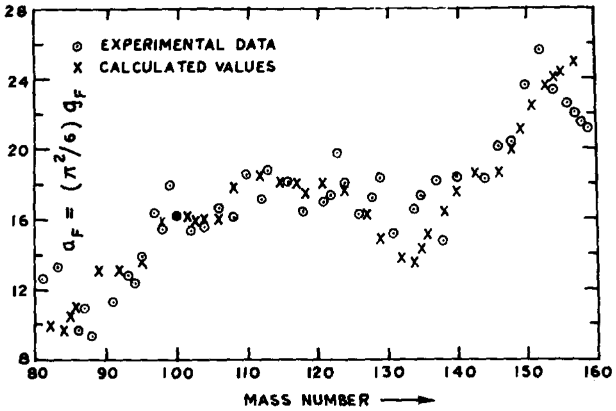

Fig. 3. The statistical level density parameter (the a-parameter) of the prompt fission fragments as a function of the prompt fragment mass number. The method of calculation of ref. [18]. The experimental data compilation of ref. [19] is also shown for comparison.

must be spent in the form of quadrupole vibration deexcitations (E2 transitions).

The entire prompt fragment deexcitation process is visualised as

$$A_{F^*} \xrightarrow[\nu_F]{\text{neutrons}} A_{F'^*} \xrightarrow[n_\gamma]{\text{gammas}} A_{F'} \qquad (2)$$

where ν_F is the number of prompt neutrons from A_{F^*} and n_γ is the number of prompt γ-rays emitted from the fragment $A_{F'^*}$ ($A_{F^*} - \nu_F = A_{F'^*}$). The highest possible value of the residual excitation ($\sim$ neutron separation energy S_n) is ~ 7 MeV for ^{252}Cf and ~ 5.5 MeV for ^{235}U + n, as predicted in figs. 1(b) and 2(b) and as found experimentally [12]; this E_γ^{max} corresponds to a single direct γ-transition from near the neutron threshold to the ground state of $A_{F'}$. On the average, however, $(E_\gamma^{max})_{av} \sim \frac{1}{2} S_n \sim 3.5$ MeV, and is the average energy available for prompt γ-decay of the fragments [13].

We now correlate the total available γ-energy E_γ^{max} with the average γ-decay energy (photon energy) E_γ and with the total number of photons n_γ in a fragment F'* from the renormalised Fermi gas model. Here we make the crucial assumptions that (1) only a cascade deexcitation of mean energy E_γ is permitted, (2) a prescribed statistical level structure of the fragments exist and (3) the deexcitation takes place by E2 transitions alone, i.e.,

$$E_\gamma^{max} = n_\gamma \cdot E_\gamma \ .$$

There are the following good experimental reasons to believe that the prompt γ-deexcitation process proceeds through a series of cascade γ-rays; (i) the measured yield of γ-rays with energy $(E_\gamma^{\rm max})_{\rm av} = \frac{1}{2}E_\gamma^{\rm max}$ is $\sim$ 100 times greater [12] than the yield with energy $E_\gamma^{\rm max}$, (ii) the measured energy-selected yield of energy $\lesssim$ 1 MeV is $\sim 10^5$ times greater than of energy $E_\gamma^{\rm max}$ [14] and (iii) it has been stated that on the average about 3 to 5 γ-rays of mean energy $\lesssim$ 600 keV are observed [15]. A cascade deexcitation of mean energy E_γ is also favoured from the following considerations: (a) fission fragments have to get a rid of the large angular momentum $l_{\rm I}$ of the fissioning nucleus I; since prompt neutrons carry away only a small fraction of $l_{\rm I}$, the relief can come only through a γ-cascade process, and (b) the quadrupole-monopole type of mutual coulomb interaction $E_{\rm q}$ as discussed earlier, is expected to give rise to the E2 type cascade γ-rays; some discussions on this point exist in the literature [16].

The well known statistical property of the level structure of the free gas is that the single particle level density g_0 near the Fermi surface ϵ_0 generates a nuclear level density ρ_0 at an excitation U_0 [17]. These quantities are interaction-modified in a real nuclear case. The necessary modifications may be evaluated from the renormalised Fermi gas model. It can be shown that the level spacing $d_{\rm F'}$ and the single particle level density $g_{\rm F'}$ of the nucleus F' is related to the free gas density g_0 [18] by

$$g_{\rm F'} = 1/d_{\rm F'} = g_{\rm n} + g_{\rm p}, \quad g_{\rm n\ or\ p} \approx g_0(1+\delta\epsilon/\epsilon_0) \tag{4}$$

including the state mixing effects and effective occupation factors in a deformed open shell (coulomb contribution added). A plot of the level density parameter $a_{\rm F}$ ($= \frac{1}{6}\pi^2 g_{\rm F}$) for the prompt fission fragments are shown in fig. 3 and are compared with the experimental data compilation of the a-parameter [19]; we note fair agreement between calculated and measured values.

A correlated set of nuclear level structure coupled to the ground state (e.g., 0^+, 2^+, 4^+, . . , in an even-even and $J^\pi + \sum_k 2k$ series with $k =$ = 0, 1, 2, . . . , in an odd-even nucleus) is often known to persist upto fairly high excitations ($\sim$ 3 - 4 MeV). Assuming this special set of correlated levels to be a set of equidistantly spaced statistical levels of spacing $d_{\rm eff}$ above the renormalised gas model Fermi surface ϵ, we note that (i) upto about $E_\gamma^{\rm max}$, levels of only one kind of parity are effective for E2 transitions and (ii) an upper limit can be set at $\sim \frac{1}{2}E_\gamma^{\rm max}$ (not $E_\gamma^{\rm max}$), as discussed below. Condition (i) gives

$$d_{\rm eff} = 2d_{\rm F'} = 2/g_{\rm F'} = 1/g_{\rm eff} \approx E_\gamma \ . \tag{5}$$

Regarding (ii), it is well known that higher rotational-vibrational groups of levels appear at $\sim$ 3 MeV and that our correlated statiscitcal levels (5) degenerate into an exponentially varying level density ρ_0 above $\sim \frac{1}{2}E_\gamma^{\rm max}$; since the number of levels between $\frac{1}{2}E_\gamma^{\rm max}$ and $E_\gamma^{\rm max}$ increases from tens to hundred-thousands, the average $d_{\rm eff}$ is so small, and the competition between E2 transition-favouring levels is so large, that it is impossible to observe the effects of special levels any more. Moreover, the electronics and the detecting counter energy selectivity are often usually biased against counting these low energy γ-rays in typical experiments [12, 14, 15]. The correlation (3) thus modifies to

$$(E_\gamma^{\rm max})_{\rm av} \approx \tfrac{1}{2}E_\gamma^{\rm max} \approx n_\gamma \cdot d_{\rm eff} \approx E_\gamma \cdot n_\gamma \ . \tag{6}$$

The number of prompt γ-rays n_γ are calculated from the correlation (6) and are shown in figs. 1(c) and 2(c). Experimental data are also shown in figs. 1 and 2 when available. We note that for figs. 1(b) and 1(c), the experimental errors have been increased by a factor of 3 on the basis of some comments of the workers [15] on ^{235}U + n. Our absolute yields n_γ agree fairly well with the measured relative γ-ray yields [14, 15].

Several phenomena compete with (6) to provide alternative paths of deexcitation of the prompt fission fragments, e.g., the delayed neutron emission, the direct $E_\gamma^{\rm max}$ transition to the ground state and other cross-over γ-rays of different multipolarities, etc.. Such delayed, weak and retarded phenomena have been assumed in the present work to make a negligible contribution to the main stream of deexcitation (6).

The experimental time resolution of $\sim 10^{-9}$ to 10^{-11} s [14, 15] 'defines' the prompt processes in γ-decay. This time scale is appropriate for allowed E2 transitions.

References

[1] R. Sarkar and A. Chatterjee, Phys. Letters 30B (1969) 313.
[2] R. Sarkar and A. Chatterjee, Phys. Rev. C1 (1970) 619.
[3] U. Mosel and W. Greiner, Z.Physik 217 (1968) 256; 222 (1969) 261.
[4] R. Sarkar, to be published.
[5] Gy. Kluge and A. Lajtai, Phys. Letters 27B (1968) 65; 30B (1969) 311.
[6] J. M. Ferguson and P.A Read, Phys. Rev. 150 (1966) 1018.

[7] F. Dickmann and K. Dietrich, Nucl. Phys. A129 (1969) 241.
[8] H. W. Schmitt, Proc. Intern. Sym. on Why and how shlould we investigate nucleides far off the stability line, Lykesil, Sweden (1966); Arkiv Phys. 36 (1966) 633; Proc. Intern. Conf. on the Physics and chemistry of fission, Vienna, 1969 (I. A. E. A., Vienna, 1969) p. 67.
[9] L. Wilets, Theories of nuclear fission (Oxford University, Oxford, 1964).
[10] S. Chatterjee, unpublished private communication.
[11] W. K. H. Panofsky and M. Phillips, Classical electricity and magnetism (Addison-Wesley, Reading, Mass. 1962) Fig. 1-3, p. 16 and Ex. 6, p. 116
[12] E. C. Maienschein, R. W. Peele, W. Zobel and T. A. Law, Second Intern. Conf. on Peaceful uses of atomic energy, Geneva, 1958 (United Nations, Geneva) Vol. 15, paper No. P/670;
F. E. W. Rau, Ann. Physique 10 (1963) 252.
[13] V. F. Apalin, Yu. N. Gritsiuk, I. E. Kutikov, V. I. Lebedev and L. A. Mikailian, Nucl. Phys. 71 (1965) 553.
[14] S. A. E. Johanson, Nucl. Phys. 60 (1964) 378; 64 (1965) 147.
[15] H. Maier-Leibnitz, H. W. Schmitt and P. Armbruster Intern. Conf. on the Physics and chemistry of fission, Salzburg, 1965 (I. A. E. A., Vienna, 1965) Vol. 2, p. 143.
[16] R. B. Leachman, Second Intern. Conf. on Peaceful uses of atomic energy, Geneva, 1958 (United Nations, Geneva) Vol. 15, paper No. P/665;
V. M. Strutinskii, Soviet Phys. JETP 10 (1960) 613.
[17] T. E. O. Ericson Advances in Phys. 9 (1960) 425.
[18] S. K. Chosh, S. Chatterjee and A. Chatterjee, to be published.
[19] E. Erba, U. Facchini and E. Seatta-Menichella, Nuovo Cim. 22 (1961) 1237;
U. Facchini and E. Saetta-Menichella, Energia Nucleare 15 (1968) 54.

* * * * *