The nucleon phase of binary fission
G. Mouze, S. Hachem and C. Ythier
Faculté des Sciences, Université de Nice, 06108 Nice cedex 2 France

Dedicated to the memory
of Professor Ileana Iori

Summary
A new description of the binary fission process is presented. The extreme brevity, of the order of $1.8 \times 10^{-25}$ second, of its main step is proved by the substitution of a mass-spectrum, having a width of about 4 mass units, to any discrete mass value. This main step is a sharing-out of nucleons, within a “nucleon-phase”, between the valence shells of the primordial cluster of the internally-dissociated fissioning system and the valence shells of the “$A = 126$ nucleon core” of the nascent heavy fragment. The formation of an “$A = 82$ nucleon core” in the nascent light fragment explains the asymmetric fission mode of the light actinide nuclei. The nucleon partition in the nucleon phase can be understood in the framework of chemical thermodynamics. The formation of an “$A = 126$ nucleon core” in the nascent light fragment of heavier fissioning systems explains the symmetric fission mode of $^{258}$Fm and that of heavier nuclei. But the new phenomenon of “barrier-free” fission, discovered in $^{258}$Fm (s.f.), plays in this system and all symmetrically fissioning superheavy nuclei a very important role.

1. Introduction
At the 2008 Bormio Meeting on Nuclear Physics, we presented some recent results concerning binary fission:
1°) The cold-fission experiment of C. Signarbieux [1] suggests that the main step of the neutron-induced fission of $^{235}$U occurs within $\sim 1.8 \times 10^{-25}$ s: this corresponds to an interaction range in nuclear matter as small as $\sim 5.4 \times 10^{-17}$ m, and to an uncertainty on the energy as great as 3.72 GeV: Its means that any fission event involves extreme conditions.
2°) According to K.F. Flynn et al.[2], the mean mass $\bar{A}_L$ of the light fission products varies linearly as a function of the mass $A_F$ of the fissioning system. This suggests that the light fragment is nothing else but the primordial “cluster”, of mass-number $A_{cl}$ (e.g. $^{28}$Ne for $^{235}$U + nth),“dressed” with nucleons taken from the $^{208}$Pb “core”.
3°) Observations made by G. Mouze on the symmetric fission of $^{258}$Fm [3] show that the fission energy $Q$ exceeds the Coulomb barrier $B_c$ for the two most energy-rich fragment pairs: this suggests that the usual “fission barrier” $B_f$ is nothing else but the “external” fission barrier $B_{c corr.}$ (i) $– Q$ (i), calculated for the most energy-rich fragment pair “i” and with $B_c$ corrected for the sphericity of the fragments. Always
positive for the light actinide nuclei, becomes for the first time negative for \(^{258}\text{Fm}\), which can, at least partially, fission barrier-free.

4) Experiments made by P. Armbruster et al. [4] and by Chizhov et al. [5] suggest the existence of an “internal” fission barrier, which appears when the internal energy of the primordial dinuclear system is not great enough for inducing its “rearrangement”.

But we announced, too, that Terrell’s equation [6]

\[ \bar{\nu} = 0.08 (A_L - 82) + 0.10 (A_H - 126), \]

(1)

giving the mean prompt-neutron yield as a function of mass for the systems \(^{233}\text{U} + n_{th}, \(^{235}\text{U} + n_{th}, \(^{239}\text{Pu} + n_{th}\) and \(^{252}\text{Cf}\) (s.f.), can be interpreted as revealing the role of an intermediary nucleon phase in asymmetric fission.

Indeed, Terrell’s equation suggests that the prompt neutrons are emitted by the valence shells of an \(A_L = 82\) nucleon core and by the valence shells of an \(A_H = 126\) nucleon core, whereas the \(A_L = 82\) and \(A_H = 126\) cores themselves do not emit any neutron, as if a nucleon phase could be created in which nucleon shells are closed at “A” = 126 in the nascent heavy fragment and at “A” = 82 in the nascent light fragment, and as if magic mass numbers, 82 and 126, could exist. And we announced that this hypothesis explains the fact that the mass yield of the light fragments decreases abruptly as soon as the mass number \(A_L\) becomes smaller than 82.

The aim of the present communication is first to show that this nucleon-phase hypothesis furnishes a complete explanation of the mass distributions observed not only in asymmetric fission (Sect.2) but also in symmetric fission (Sect.3).

The aim of the present communication is further to show that the main step of binary fission can be understood in the frame of the laws of chemical thermodynamics (Sect.4).

In Sect.5, we examine the role played by the new phenomenon of barrier-free fission not only in the fission of \(^{258}\text{Fm}\), but also in that of superheavy nuclei, such as \(^{286}(112)\)*, which fission symmetrically according to the laws of the nucleon phase.

2. Nucleon phase and asymmetric fission

2-1 The width of the mass distributions

In the two-step model of fission [7], the maximum number of nucleons which can be transferred from core to cluster was equal to 76, i.e. to the number of nucleons, 32 protons and 44 neutrons, of the whole valence shell of the deep –lying \(^{132}\text{Sn}\)-core present in the primordial \(^{208}\text{Pb}\) core.

In the nucleon-phase model, which is now presented, the maximum number of transferred nucleons is 82. The reason is that an \(A = 126\) nucleon-core is created in the \(^{208}\text{Pb}\)-core, as soon as it collides with its cluster, and that the nucleons surrounding this new core behave like valence nucleons, which can be transferred to the primordial cluster; and their number is: 208 - 126 = 82.

Consequently, the greatest value of the mass number \(A_L\) of the light fragment can be
\[ A_{L}^{\text{MAX}} = A_{\text{cl}} + 82 \]  
(2)

instead of \( A_{\text{cl}} + 76 \); and the smallest value can now be
\[ A_{L}^{\text{MIN}} = 82, \]  
(3)

because it is necessarily that of the \( A = 82 \) nucleon-core, which is created in the nascent light fragment, in the extreme conditions of the nucleon phase.

Thus the width of the region of appreciable yield is precisely limited to the value
\[ \Delta A_{L} = A_{L}^{\text{MAX}} - A_{L}^{\text{MIN}} = A_{\text{cl}}, \]  
(4)

and this holds also for the distribution of the heavy fragments: \( \Delta A_{H} = A_{\text{cl}} \) since
\[ A_{H}^{\text{MIN}} = 126 \]
\[ A_{H}^{\text{MAX}} = 126 + [82 - (82 - A_{\text{cl}})]. \]

Eq.(4) holds not only for the system \(^{235}\text{U} + n_{\text{th}}\), as shown in fig.1, where \( \Delta A = 28 \) u, but for all light actinide nuclei. So, it can be considered as a rule, dictated by the nucleon-phase “model”. As another example, the region of appreciable yield for the system \(^{239}\text{Pu} + n_{\text{th}}\) (fig.2) extends from \( A_{L} = 82 \) to \( A_{L} = 114 \), and from \( A_{H} = 126 \) to \( A_{H} = 158 \); its width is equal to 32 u, since \( A_{\text{cl}} \), the mass number of the primordial cluster, \(^{32}\text{Mg}\), is equal to 32. The region of appreciable yield of all actinide nuclei can be represented by the hatched area of fig.2 (on the left) \cite{8}.

Let us now show that “asymmetric” fission is a consequence of the laws of nucleon phase.

Indeed, for all actinide nuclei lighter than \(^{252}\text{Cf}\), it is not possible to form a single fragment having a mass equal to \( A_{F}/2 \), i.e. half the mass of the fissioning nucleus.

Even for \(^{252}\text{Cf}\), only one light fragment of the region of appreciable yield can have a mass-value equal to \( A_{F}/2 \), namely \( A_{L}^{\text{MAX}} = 44 + 82 = 126 \), precisely equal to 252/2, in spite of the fact that there are 44 possible \( A_{L} \) mass-values in this region of appreciable yield, extending from \( A_{L}^{\text{MIN}} = 82 \) to \( A_{L}^{\text{MAX}} = 126 \), and having a width equal to the mass number 44 of the primordial cluster \(^{44}\text{S}\).

2-2 The new expression of the law of Flynn et al..

The mean mass of the heavy fission products has been found to be constant and equal to \( \sim 138 \) for \(^{233}\text{U} + n_{\text{th}}, \text{ }^{235}\text{U} + n_{\text{th}}\) and \(^{239}\text{Pu} + n_{\text{th}}\); it is the law of A.C. Wahl \cite{9}.

This suggests that the mean mass \( \overline{A}_{H} \) of the heavy fragments is equal to about 140. It is noteworthy that even the mean charge \( \overline{Z} \) of the heavy fission fragments has been found constant, and equal to \( \sim 54 \) \cite{10}.

Let us show that the new expression of Wahl’s law can now be written:
\[ \overline{A}_{H} = 126 + 14 \]  
(5)

whereas the new expression of the law of Flynn et al. is now
\[ \overline{A}_{L} = A_{\text{cl}} + 68. \]  
(6)
Indeed, eq.(5) is a consequence of the existence of the nucleon phase and of the constancy, 140, of $\overline{A_H}$.

And eq.(6) is a consequence of the nucleon-phase, in which a constant number 208 - 126 = 82 of nucleons are transferred from core to cluster. But, if 14 of them, according to eq.(5), remain in the valence shells of the $A_H = 126$ nucleon core, only 82-14, i.e. “68”, are, on an average, transferred to the primordial cluster.

It is noteworthy that in a first attempt made by G. Mouze [11] for understanding the linear law of Flynn et al., a value of $\overline{A_L}$ equal to 66.7, close to the new value of 68, had already been found for the mean number of nucleons transferred from core to cluster in the n-induced fission of $^{235}$U.

The greater concentration of transferred nucleons on the side of the cluster can be understood without reference to the nucleon phase model, since these nucleons are expected to have a greater binding energy in the valence shells of the cluster than in those of an $A_H = 126$ core. But in the framework of the nucleon-phase model, it may be understood, too, as a consequence of the great tendency of the valence shells of the cluster to close at $A_L = 82$.

In fig.2, the variation of $\overline{A_L}$ as a function of $A_F$ is represented by a straight line parallel to the variation of $A_{cl}$, since $\overline{A_L} - A_{cl} = 68$.

It is noteworthy that $\overline{A_L}$ coincides with the mass number $A^* = 82 + (\Delta A_L/2)$ of the middle of the region of appreciable yield only for the system $^{235}$U + $n_{th}$; this could be seen in fig.1, after correction for the prompt neutron-emission.

But this situation is exceptional. For the system $^{233}$U + $n_{th}$, $\overline{A_L}$ is equal to 94, is also smaller than $A^*$, equal to 95, whereas, for the system $^{252}$Cf (s.f.), $\overline{A_L}$ is equal to 112, is also much greater than $A^*$, equal to 104.

Anyway, the profile of the mass distributions of the light and heavy fragments, and that of the products -- shown in fig.1 for the neutron-induced fission of $^{235}$U -- is essentially determined by the tunnel effect.

In fact, as this will be demonstrated in Sect. 3, the fission of all nuclei lighter than $^{258}$Fm is “confined” by the Coulomb barriers of all their possible fragment pairs. Consequently, the extremely small fission yield in the vicinity of the limits of the region of appreciable yield results from the too great number of fragment pairs for which $Q$, the fission energy, is much smaller than $B_c$, their Coulomb barrier.

3. Nucleon phase and symmetric fission

Let us show that the nucleon phase model explains the appearance of the symmetric fission mode in nuclei heavier than $^{252}$Cf.

Indeed, something new appears already in this $^{252}$Cf: Addition of 82 nucleons to its $^{44}$S cluster leads to the formation of a closed $A = 126$ shells (fig.2). Can the new $A = 126$ nucleon core compete with the $A = 82$ core? Moreover, the regions of appreciable yield of the light and heavy fragments become here, for the first time, adjacent, instead of being well separated. However, their width is still equal to $A_{cl}$ mass units, i.e. to 44 u.
But as soon as an $A_L = 126$ core can exist in a nucleus heavier than $^{252}$Cf, a new situation is created.

The expected values of $A_L^{\text{MIN}}$ and $A_L^{\text{MAX}}$ are now:

$$A_L^{\text{MIN}} = 126,$$

$$A_L^{\text{MAX}} = A_{cl} + 82.$$  \hspace{1cm} (7)  \hspace{1cm} (8)

Let us consider what happens in a nucleus such as $^{258}$Fm (fig. 3). These values are now:

$$A_L^{\text{MIN}} = 126,$$

$$A_L^{\text{MAX}} = A_{cl} + 82 = 50 + 82 = 132,$$

and the width of the region of appreciable yield becomes now much **narrower** than in asymmetric fission: $\Delta A_L (^{258}\text{Fm}) = 132 - 126 = 6 \text{ u}!$

*It is the closure of the $A = 126$ nucleon shell in the light fragment that causes the appearance of the symmetric fission mode!*

The width of the region of appreciable yield is now given, more generally, by the relation

$$\Delta A_L = A_L^{\text{MAX}} - A_L^{\text{MIN}} = \left[ (A_{cl} + 82) - 126 \right] \text{ u},$$

$$= (A_{cl} - 44) \text{ u}. \hspace{1cm} (9)$$

Fig. 3 shows that the two regions of appreciable yield of light and heavy fragments are no more separated: they coincide. For $^{258}$Fm, they extend from $A_L = 126$ to $A_L = 132$, and from $A_H = 132$ to $A_H = 126$.

Fig. 3 further shows that the region of appreciable yield predicted by the nucleon-phase model for nuclei heavier than $^{252}$Cf is the hatched area on the right.

However, it may now be asked whether there still exists an asymmetric mass distribution, and whether the mean value $\overline{A_L}$ of the corresponding light fragments is still equal to $A_{cl} + 68$.

An answer to this question should require a careful analysis of the pedestal of the rather intense peak at $A = 129$ in the mass spectrum of $^{258}$Fm (s.f.) . Moreover, it should take into account the appearance of a new phenomenon, that of a "barrier-free fission", to which Sect. 5 will be devoted.

4. Can nuclear fission be described by the laws of chemical thermodynamics?

Let us now show that eqs. (5) and (6) can be interpreted in this framework.

Indeed, they mean that, in the rearrangement of the primordial dinuclear system of asymmetrically fissioning systems, a constant number of nucleons become distributed between the valence shells of the $A_H = 126$ nucleon core and the free states of the cluster in such a manner that the ratio:

$$\left[ (\text{Mean number of nucleons remained on the } A_H= 126 \text{ core}) \right] / \left( \text{Mean number of nucleons really transferred to the cluster} \right)$$
remains constant and equal to $C = 14/68 = 0.206$.  

It is noteworthy that this situation is similar to that encountered in the study of the distribution of one and the same body between two unmiscible solvents. For such a distribution W. Nernst found in 1891 the following law:

$$\frac{\text{concentration in solvent I}}{\text{concentration in solvent II}} = C$$  

This similarity suggests the following interpretation: In the rearrangement of the dinuclear system of fissioning nuclei the variations $d\mu_I$ and $d\mu_{II}$ of the chemical potential $\mu$ of the 82 transferrable nucleons in the valence shells (I) of the $A_H = 126$ nucleon core and in those (II) of the primordial cluster should be equal at equilibrium.

5. The barrier-free fission of $^{258}$Fm and superheavy nuclei.

5-1 The $^{258}$Fm case.

If the region of appreciable yield predicted by the nucleon-phase model for $^{258}$Fm has a width of 6 u, it involves the following fragment pairs: $^{126}$Sn - $^{132}$Sn, $^{127}$Sn - $^{131}$Sn, $^{128}$Sn - $^{130}$Sn and $^{129}$Sn - $^{129}$Sn. Other charge-splits can be neglected, because the uncertainty $\Delta Z$ is equal to $4(Z/A) = 4(100/258) = 1.55$ u, i.e. very small, and because they are not as much favored energetically as the Sn/Sn split.

However, G. Mouze showed in 2005 [3] that only two of these four Sn-Sn fragment pairs are responsible for the considerable yield discovered at symmetry by D.C. Hoffman et al. in 1977 [12]; these two pairs are $^{128}$Sn - $^{130}$Sn, with $Q = 253.794$ MeV and $B_c^{corr.} \sim 252.191$ MeV, and $^{126}$Sn - $^{132}$Sn, with $Q = 252.895$ MeV and $B_c^{corr.} \sim 252.205$ MeV. The "sphericity correction" [3] for the tin nuclei reaches $\sim + 11.49$ MeV for the pair $^{128}$Sn - $^{130}$Sn, as can be estimated by a comparison of the fission properties of the three fermium nuclei with $A = 256, 257$ and 258. The two other pairs have $B_c$-values greater than their fission energy. It is the absence of any Coulomb barrier for the formation of the pairs $^{128}$Sn - $^{130}$Sn and $^{126}$Sn - $^{132}$Sn that explains their high yield.

This situation leads to the following consequences:

--First, the experimental full-width-at-half-maximum (f.w.h.m.) of the peak at $A = 129$, found to be equal to 8 u by D.C. Hoffman et al., can be justified: this peak must be considered as resulting from the addition of four Gaussian distributions having a width of 4u, centered on the $A$-values 126, 128, 130 and 132.

--Secondly, the comparison of the experimental f.w.h.m. of 8 u to the width $\Delta A$ of only 6u predicted by the nucleon-phase model suggests the following relation:

$$\text{f.w.h.m.} \sim (\Delta A + 2) u,$$

as a consequence of the uncertainty on mass.
Thirdly, the absence of any Coulomb barrier for the formation of these fragment pairs further means that their energy can be as great as the maximum energy released by the fission reaction, without any reduction resulting from the “thermalization” caused by internal collisions occurring in a “confined” fission process. And this explains why E.K. Hulet et al. [13] have found that the energy spectrum of $^{258}$Fm is in reality complex, with a component having the maximum energy delivered by the fission reaction. In other words, this explains the “bimodality” of the symmetric fission of $^{258}$Fm.

It is noteworthy that the low-energy component of the energy spectrum of $^{258}$Fm constitutes an indication that the asymmetric fission mode still survives and contributes to a low-intensity pedestal, spreading in reality over a very great mass interval, because this low-energy component cannot be due to the sole, still confined $^{127}\text{Sn}-^{131}\text{Sn}$ and $^{129}\text{Sn}-^{129}\text{Sn}$ fragment pairs.

In conclusion, the nucleon $-$phase model predicts that the region of appreciable yield of $^{258}$Fm extends from $A = 126$ to $A = 132$. But it is the phenomenon of barrier-free fission that explains that only two of the four possible fragment pairs filling this $\Delta A$-interval contribute to the considerable yield at symmetry in the mass spectrum and that they have the maximum energy.

5-2 The barrier-free symmetric fission mode of superheavy nuclei.

Let us consider the case of the spontaneous fission of $^{286}(112)^*$, formed by fusion reaction at $E_{\text{exc}} \sim 33$ MeV [14]. The nucleon-phase model predicts a region of appreciable yield for its symmetric mode having a width of 34 u. Indeed, its limits are $A_L^{\text{MIN}} = 126$,

$A_L^{\text{MAX}} = 78 + 82 = 160$,

since the primordial cluster is $^{78}\text{Zn}$.

This statement holds if the uncertainty on the mass is neglected. Otherwise, the expected width should be of the order of 36 u, on account of eq. (12).

However, it is the phenomenon of barrier-free fission that decides on the experimental fission yield. So, it is interesting to try to simulate the symmetric mass distribution resulting from this phenomenon. It may be assumed that the yield is proportional, for each $A$-value, to positive differences such as $\Delta = Q (i) - B_c (i)$, corresponding to all possible fragment pairs $i$ having a fragment of mass $A$.

Let us consider the following charge splits of $^{286}(112)^{\text{g.s.}}$:

$\text{Ba/Ba, Cs/La, Xe/Ce, I/Pr, Te/Nd, Sb/Pm, Sn/Sm, In/Eu, Cd/Gd, Ag/Tb, Pd/Dy, Rh/Ho et Ru/Er.}$

For each charge-split, a double-humped distribution is obtained, if all corresponding mass splits $i$ are considered. But the addition of these partial mass distributions leads to the symmetrical mass spectrum of fig.4.

A strong odd-even effect is observed.
It can be verified that between $A = 125$ and $A = 161$, the neglected charge splits do not affect the profile of the spectrum, and that no mass data are lacking for the charge splits taken into consideration. No sphericity correction was applied to the $B_c$-values, because, for a comparison with the experimental mass spectrum obtained by M.G. Itkis et al. [14], the positive differences playing a role are not the values of $\Delta = Q(i) - B_c(i)$, but those of $\Delta^* = Q^*(i) - B_c(i)$, where $Q^*(i) \sim [Q(i) + \sim 33 \text{ MeV}]$, so that the correction plays a negligible role. And no correction was made for the uncertainty on the masses.

Interestingly, the obtained spectrum (fig. 4) is made of two overlapping peaks, culminating at $A = 133$ and $A = 152$, as in the spectrum reported by M.G. Itkis et al. (fig. 5).

However, the width of each of these two peaks is clearly greater than that observed by M.G. Itkis et al., since there is no dip at symmetry in the spectrum of fig.4, resulting from the addition of these two peaks.

The discrepancy between the two mass-spectra clearly results from the fact that the construction of fig.4 on the sole basis of the positive $(Q - B_c)$-values did not take into account the fact that the region of appreciable yield in $^{266}(112)$ is limited by the nucleon phase model to the mass-interval $\Delta A = 160 - 126 = 34 \text{ u}$, as indicated in fig.4.

It may be concluded that the experimental mass spectrum of $^{266}(112)^*$ reported by M.G. Itkis et al. (fig.5) results from a barrier-free symmetric fission mode occurring in the limits fixed by the laws of the nucleon phase.

Very similar remarks can be made in the case of the symmetric fission mode of $^{266}$Hs, for which the nucleon phase model predicts a width of 14 u, since the limits of the region of appreciable yield, as shown in fig. 3, are: $A_{\text{MIN}} = 126$, and $A_{\text{MAX}} = 58 + 82 = 140$, the primordial cluster being $^{58}$Fe.

A similar construction, taking into account a great number of charge splits, shows that the mass distribution resulting from the barrier-free mode of fission is neither narrowly symmetric as in the case of $^{258}$Fm, nor double-humped, as in the case of $^{266}(112)$, but now broadly symmetric.

It is noteworthy that, in these three cases, there is no reduction of yield in the vicinity of the limits of the region of appreciable yield as it was observed in the asymmetric mode of the light actinide nuclei (fig.1) as a consequence of the “tunnel effect”: due to the phenomenon of barrier-free fission, there is no longer any observable “confinement”.

6. Conclusion

The nucleon-phase hypothesis furnishes a coherent interpretation of several experimental facts, which were unexplained up to now:

-- The width of the region of appreciable yield of fragments of the asymmetric fission mode of the light actinide nuclei;
The width of the region of appreciable yield of fragments of the symmetric fission mode of nuclei heavier than $^{252}$Cf and of superheavy nuclei;
--- The zero-yield of prompt neutrons of fragments of the asymmetric mode with $A = 82$ and $A = 126$;
--The linear increase of this prompt-neutron yield above $A = 82$ and $A = 126$.

The nucleon-phase hypothesis furnishes a deeper understanding of the law of Flynn, and leads to an interpretation of the rearrangement reaction of the main step of fission in the framework of chemical thermodynamics: If the equilibrium could be reached, the sharing-out of the nucleons would follow a Nernst distribution law.

This hypothesis seems to deserve a promotion to the rank of a model: It explains for the first time why the neutron-induced fission of the light actinide nuclei can only be asymmetric, and why fission becomes symmetric as soon as the mass of the light fragments can become greater than 126.

It might be asked whether the "nucleon" of such a nucleon-phase could become a "third" constituent of the atomic nucleus, after the proton, discovered in 1919 by Rutherford, and the neutron, discovered in 1932 by Chadwick. The answer might be yes, if one considers that these three particles share the same property of getting organized, each of them in their own phase, in shells governed by the same "magic" particle-numbers. However, this "nucleon" can be only an "exotic" constituent, since it can exist only in the extreme conditions described above.

The nucleon-phase hypothesis raises several interesting questions.

For example, it may be asked what happens to the quarks as the distinction between proton and neutron disappears.

This example shows that even the question of the true nature of charge can no more be avoided.

It may further be asked what happens at the end of the nucleon phase, as the fragments are back made of protons and neutrons. Can this change be the cause of the double giant dipole resonance, responsible, according to G. Mouze, of one of the emission modes of ternary charged particles, the “orthogonal” mode, and responsible, too, of the prompt-neutron emission [17]?

An answer to some of these questions will be given in a forthcoming paper [18].

7. Acknowledgements.

We thank Professor Renato A. Ricci for his continued interest in our work and for valuable discussions.

References


Fig. 1: Effect of the nucleon phase on the mass distribution of the fission products of $^{235}\text{U} + n_\text{th}$. It decides on the width of the regions of appreciable yield, which is equal to $A_c$, in mass units (u). $A_c$ is equal, here, to 28, the mass number of the primordial cluster $^{28}\text{Ne}$. The fission yields are taken from K. F. Flynn and L. E. Glendenin (ANL Report N°4479, 1970). The mass distribution of the "fragments", after correction for the prompt-neutron emission, differs only slightly from this figure (cf., e.g., R. Vandenbosch and R. Huizenga, Nuclear Fission, Academic Press 1973, p. 321).

Fig. 2: Transfer of 82 nucleons from core to cluster in the fission of $^{239}\text{Pu} + n_\text{th}$ according to the nucleon-phase model. The region of appreciable yield for the asymmetric fission of the light actinide nuclei is represented by the hatched area on the left.
Fig. 3: Transfer of 82 nucleons from core to cluster in the spontaneous fission of $^{258}$Fm according to the nucleon-phase model. The region of appreciable yield extends from $A=126$ to $A=132$; it is included in the hatched area corresponding to the symmetric fission mode of heavy actinide nuclei and superheavy nuclei, on the right.

Fig. 4: Construction of the mass spectrum of $^{256}$U(112).

Crosse squares: contributions of the mass-splits from $^{152}$Ba/$^{134}$Ba to $^{144}$Ba/$^{142}$Ba; from $^{149}$Cs/$^{137}$La to $^{144}$Cs/$^{142}$La; from $^{147}$Xe/$^{139}$Ce to $^{144}$Xe/$^{142}$Ce and $^{144}$I/$^{142}$Pr.

Full circles: contributions of all other mass splits.

Open squares: sum of overlapping branches.
Fig. 5: Upper frames, double humped mass distribution of the symmetric fission mode of the superheavy nuclei $^{286}(112)^*$, $^{232}(114)^*$ and $^{256}(116)^*$. The region of appreciable yield extends from \( A = 126 \) to \( A = A_{\text{cl}} + 82 \), also from 126 to 160 for $^{286}(112)^*$, 166 for $^{232}(114)^*$ and 170 for $^{256}(116)^*$ according to the nucleon-phase model. This distribution stands out against an intense background resulting from the phenomenon of "cluster-fission" [16], which itself results from the existence, in any fissile nucleus, of a core-cluster system [17], here essentially $^{208}$Pb- ($^{78}$Zn, $^{84}$Ge and $^{86}$Se). [by courtesy of Prof. M.G. Itkis, J.I.N.R., Dubna, 2001].