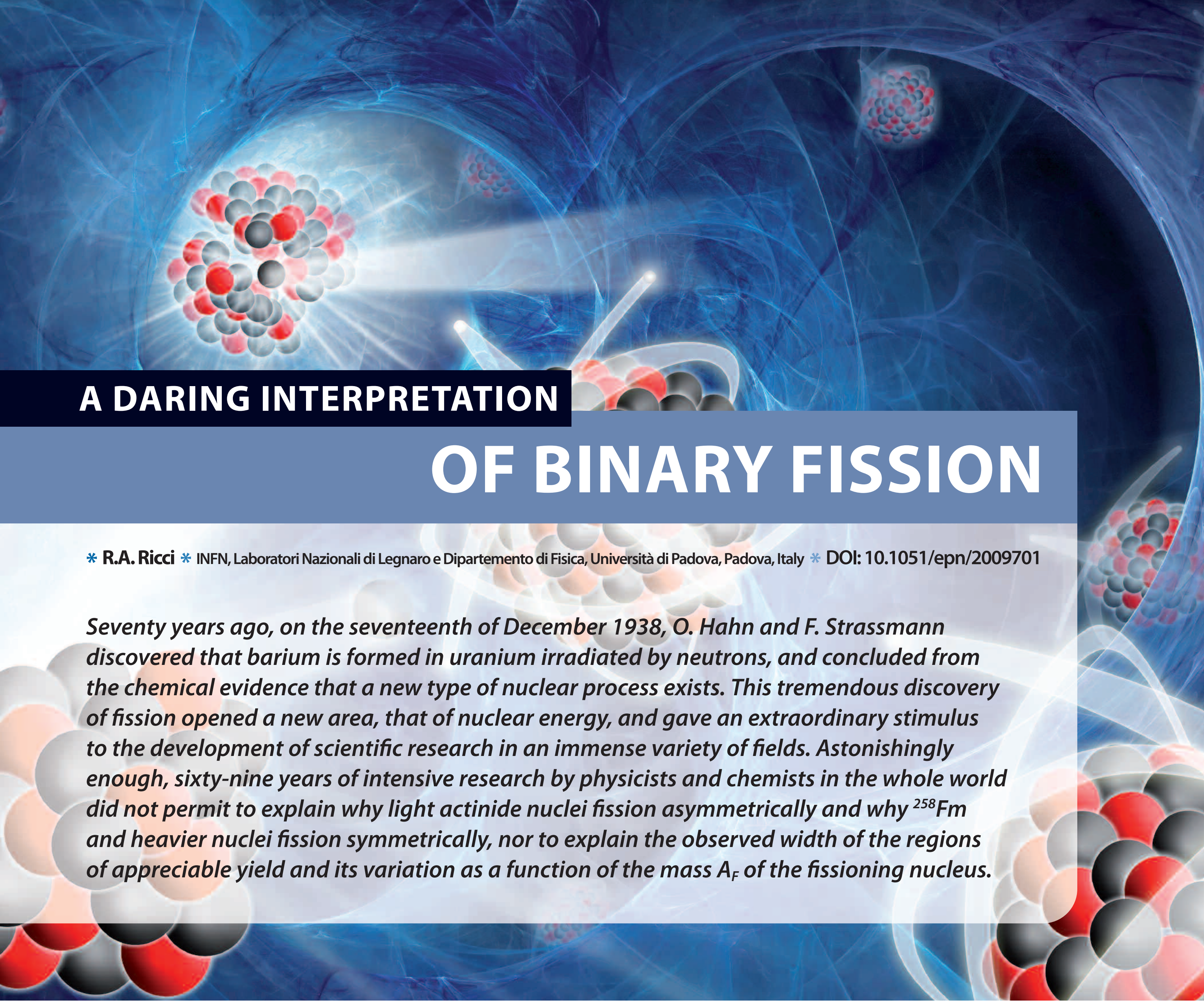

▲ A concept image of the process of nuclear fission of uranium atoms. © iStockPhoto

A DARING INTERPRETATION OF BINARY FISSION

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Seventy years ago, on the seventeenth of December 1938, O. Hahn and F. Strassmann discovered that barium is formed in uranium irradiated by neutrons, and concluded from the chemical evidence that a new type of nuclear process exists. This tremendous discovery of fission opened a new area, that of nuclear energy, and gave an extraordinary stimulus to the development of scientific research in an immense variety of fields. Astonishingly enough, sixty-nine years of intensive research by physicists and chemists in the whole world did not permit to explain why light actinide nuclei fission asymmetrically and why ^{258}Fm and heavier nuclei fission symmetrically, nor to explain the observed width of the regions of appreciable yield and its variation as a function of the mass A_F of the fissioning nucleus.

Now, after a long wait, a quite new hypothesis, able to live up to this expectation, has recently been formulated. But by its real nature, this hypothesis is much more than just an answer to the above questions: Its novelty is that it assumes the existence of a new state of nuclear matter, "the nucleon phase". The nucleon of such a phase could be a "third constituent" of the atomic nucleus, to be added to the proton of Rutherford and to the neutron of Chadwick …if it could exist other than in very extreme conditions.

This hypothesis is made of several elements (I through VI). Let us examine them successively (a), and compare them every time with possible arguments in their favor (b).

Reaction time of the major step

I-a This hypothesis first concerns the "reaction time" Δt of the major step of the fission process. This time should be as short as $1.77\,10^{-25}$s. According to the energy-time uncertainty relation $\Delta E.\Delta t \geq \hbar$, this means that any discrete mass value should be replaced by a "mass spectrum", having a width of 4 atomic mass units (u); it means furthermore, that an energy as large as 3.72 GeV should be available, and a temperature as high as 10^{13} K, *i.e.* 10^5 times higher than the temperature needed for the onset of a thermonuclear reaction, should be reached.

I-b In favor of this almost dismaying hypothesis, C. Ythier and G. Mouze, of the Chemistry Department of the University of Nice, France, have since 1991 found several arguments. They first found clear evidence, in the slope of the mass distribution of the fission of ^{235}U induced by thermal neutrons, that this distribution, in the region A ~132, can be obtained by adding Gaussian distributions centered on A = 132, 133 and so on and having a width of 5u; but they had not taken into account the very small contribution of symmetric fission at thermal energies [1]. In 1992, in their study of the fine structure discovered at Saclay by C. Signarbieux in the mass distribution of the same fissioning system (but obtained in the conditions of a "cold fission" experiment [2]) they found again clear evidence that the uncertainty in the mass is equal, more precisely, to 4u. Later on, they found another opportunity to verify this

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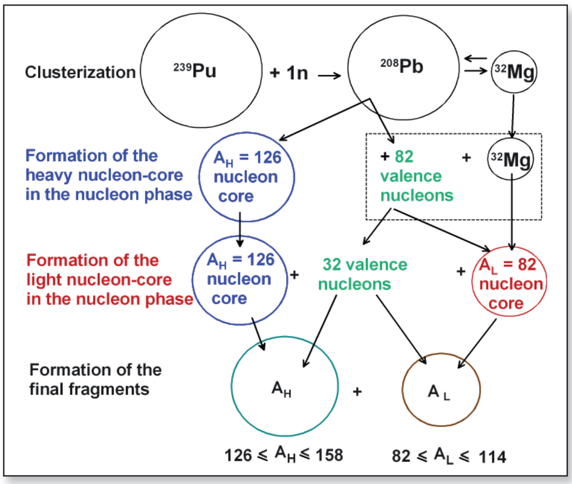


▶ FIG. 1: Description of the asymmetric fission of ^{239}Pu + nth in the nucleon-phase model by the sharing-out of a number of valence nucleons equal to A_{cl} between the nucleon cores.

value of 4u. They found that the width of 8u of the mass distribution of ^{258}Fm measured by D.C. Hoffman could be obtained by adding four Gaussian distributions centered on A = 126, 128, 130 and 132, if their width is taken equal to 4u. But recently Ythier and Mouze realized that the extreme brevity of the fission process is related to its localization in the extremely narrow region of space occupied either by the valence shells of the deep-lying ^{132}Sn core of the fissioning nucleus, or better by the valence shells of a now postulated "A = 126 nucleon core" of the nascent heavy fragment [see II-a]. Indeed, the width Δl of this region of space should be as small as only 5.3×10^{-17} m [3] and correspond to a minimum reaction time $\Delta t = \Delta l/c$ of 1.77×10^{-25} s.

The nucleon phase hypothesis

II-a As a consequence of these extreme conditions, it is further assumed that the distinct proton phase and neutron phase, which coexist in ordinary nuclear matter, disappear and are replaced by a unique "nucleon phase". Here the distinction between proton and neutron is abolished, but the nucleons form closed shells for the same magic numbers as those of the proton- and neutron-phases, in particular for A = 82 and A = 126, as if "magic mass numbers" should exist: the organization of matter in closed "shells" should be a universal law!

II-b The strongest argument in favor of the existence of a nucleon phase is the equation of James Terrell [4], which was never explained so far:

$$\overline{\nu} = 0.08\,(A_L - 82) + 0.10\,(A_H - 126), \qquad (1)$$

giving the mean value of the prompt–neutron yield of systems as different as ^{233}U + n_{th}, ^{235}U + n_{th}, ^{239}Pu + n_{th} and ^{252}Cf as a function of the mass numbers A_L and A_H of the light and heavy fission fragments, respectively.

In a communication at the 46th International Winter Meeting on Nuclear Physics [3] held in Bormio in January 2008, Ythier and Mouze pointed out that the formation, in the nascent light and heavy fragments, of an A = 82 nucleon core and of an A = 126 nucleon core, surrounded by their valence nucleons, could explain 1°) why no prompt neutron is emitted by a fragment having a mass number equal to 82 or 126 and 2°) why the prompt neutron yield increases approximately as a function of the mass number A_L or A_H for A > 82 and A > 126.

Nature of the rearrangement

III-a The hypothesis in question implies that an "ignition step" precedes the step of the nucleon phase. As heavy nuclei have a great tendency to dissociate internally with a great energy-release, *e.g.* 59.49 MeV for ^{235}U + n_{th}, this ignition step can be that of the "clusterization". Indeed, this energy is large enough for inducing a kind of "core-cluster collision".

The hypothesis is further that this collision creates in the heavy part of the "dinuclear system" an "A = 126 nucleon core", and that the 208-126 = 82 "extra-nucleons" can be partially transferred from this core to the primordial cluster. There, this transfer allows the formation of an "A = 82 nucleon-core". However, in a fissioning system such as ^{252}Cf, and in heavier systems, the transfer of nucleons can lead to the formation of an "A_L = 126 nucleon-core": It is the closure of such a shell in the nascent light fragment which explains the occurrence of the "symmetric" fission mode.

III-b There are several arguments in favor of the clusterization of the fissioning system. One of them was put into evidence by Ythier and Mouze [5] as far back as 1988; it is the law of Flynn, Glendenin *et al.*, according to which "the mean mass of the light fragments varies linearly as a function of the mass A_F of the fissioning system" [6]. Indeed, this law was then interpreted as a law of formation of the light fragment by the transfer of an almost constant number of protons and neutrons from a ^{208}Pb core to its cluster, of mass A_{cl}.

An argument in favor of the creation of an A_L = 82 nucleon core is furnished by the mass spectrum of the light fragments [7]. One observes that the fission yield decreases abruptly below A = 82, as if the valence shells of the primordial cluster had a tendency to form a closed A = 82 nucleon shell with the nucleons released by the nascent heavy fragment (where an A = 126 nucleon core has been formed), as shown by Ythier *et al.* at the Strasbourg Meeting of May 2008.

But the best argument for these A = 82 and A = 126 nucleon cores is the observed "width" of the mass distribution of the light or heavy fragments. Ythier *et al.* have demonstrated that, if the broadening of the distribution due to the uncertainty in the mass is neglected, this width must be equal to exactly "A_{cl}" u in asymmetric fission, and to exactly $(A_{cl} - 44)$ u in symmetric fission. Indeed, this width is equal to $\Delta A_L = A_L^{MAX} - A_L^{MIN}$ for light fragments; so it must be equal either to $(A_{cl} + 82) - 82$ in asymmetric fission, or to $(A_{cl} + 82) - 126$ in symmetric fission.

But if the broadening due to the uncertainty on the mass is taken into account, these two widths become $(A_{cl} + 2)$u and $[(A_{cl} - 44) + 2]$u, respectively, as is observed experimentally. For example, for the spontaneous fission (s.f.) of ^{258}Fm in which $A_{cl} = 50$, one finds a width of only 6 +2 = 8u, as was discovered, in 1977, by D.C. Hoffman [8] .
One sees that the shell closure at A = 126 in the nascent light fragment explains the "narrow symmetric" mass distribution of ^{258}Fm (s.f.). So it explains the appearance of symmetric fission! And the nucleon-phase hypothesis explains, at the same time, the asymmetric and the symmetric fission mode!

A distribution law for 82 nucleons

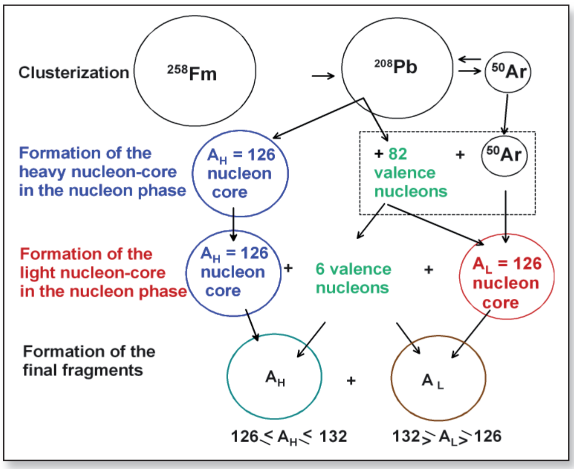
IV-a The nucleon–phase hypothesis allows to describe the main step of the fission reaction as a simple chemical process: it is the distribution of 82 nucleons between two different valence shells, those of the primordial cluster, and those of the $A_H = 126$ nucleon core of the nascent heavy fragment. And for the now well-known asymmetrically-fissioning systems, it can be characterized by a constant "distribution coefficient".
IV-b The argument in favor of this very new point of view is furnished by the law of Wahl. In 1965, A. C. Wahl, co-discoverer of plutonium, pointed out that the mean mass of the heavy "fission product" is constant and equal to ~ 138 u for fissioning systems as different as ^{233}U + n_{th}, ^{235}U + n_{th} and ^{252}Cf (s.f.) [9] . Nowadays, and for fission fragments, this constant value is taken $\overline{A_H}$ = 140u. This fact can be interpreted as follows: on an average, and whatever the fissioning system may be, 140 - 126 = 14 nucleons remain in the heavy fragment. But the number of nucleons to be distributed is constant and equal to 208 – 126 = 82. So, on an average, the number of nucleons remained in the valence shells of the primordial cluster is 82 -14 = 68. Ythier and Mouze concluded that, on the average, the mean mass of the light fragment $\overline{A_L}$ is equal to $(A_{cl} + 68)$u: it is the modern expression of the linear law of K.F. Flynn, L.E. Glendenin *et al.* [6]. But this result can also be written as follows: "the ratio of the mean number of nucleons remaining on the $A_H = 126$ core to the mean number of nucleons transferred to the primordial cluster A_{cl} is constant, and equal to 14/68 = 0.206". Thus it is nothing else but a Nernst-distribution law, similar to that established in 1891 for describing the distribution of one and the same body between two unmiscible liquids [10].

The phenomenon of barrier-free fission

V-a Nowadays it is no longer possible to correctly describe the symmetric-fission mode without referring to the discoveries made in 2005 by Mouze [11]. First, ^{258}Fm and heavier nuclei can fission "barrier -free", because, in these nuclei, several fragments pairs have a fission energy large enough for overcoming their own Coulomb barrier; this increases the fission yield of such pairs considerably. Secondly, this situation leads to the definition of an "external" fission barrier B_C^f as being the difference between the Coulomb barrier $B_c(i)$ of a given pair i and the fission energy $Q_{tot}(i)$ of this pair. As the most energy-rich fragment pairs contain "spherical" nuclei such as Sn-nuclei, a "sphericity correction" has to be applied to their $B_c(i)$. Ythier and Mouze found that the usual fission barrier B^f is nothing else but the external fission barrier of the most energy-rich fragment pair after sphericity correction: B^f can now be calculated without reference to a model! Third, the barrier-free fission decides on the "profile" of the mass distribution of all heavier and superheavy fissioning systems, in the limits determined by the nucleon phase.

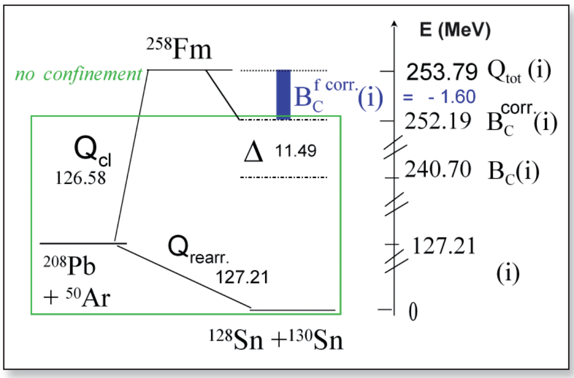
The **nucleon-phase hypothesis** provides a joint explanation of the **most enigmatic** experimental facts of **binary fission**

V-b All fragment pairs of all actinide nuclei lighter than ^{258}Fm have a positive $B_C^{f\,corr.}$-value, their corrected Coulomb barriers being greater than their fission energy: the fission of these nuclei is "confined".
In ^{258}Fm, in the region of appreciable yield predicted by the nucleon phase, having a width of 6u, only two pairs, ^{128}Sn-^{130}Sn and ^{126}Sn-^{132}Sn have a *negative* $B_C^{f\,corr.}$. The two other fragment pairs, ^{127}Sn-^{131}Sn and ^{129}Sn-^{129}Sn, have a positive $B_C^{f\,corr.}$–value. Thus it may be concluded that the high yield measured in the peak at symmetry by Hoffman in 1977 [8] was due essentially to these two most-energy-rich pairs ^{128}Sn-^{130}Sn and ^{126}Sn-^{132}Sn. This explains also the presence of a high-energy component in the energy spectrum reported by E.K. Hulet *et al.* [12]. The lower-energy component can be explained by the "thermalization" of the other still confined pairs.
For heavy symmetrically fissioning nuclei, Ythier et al. made the observation that the different profiles of their mass distributions, either narrow and almost Gaussian, *e.g.* for ^{258}Fm, or broadly symmetric [13], *e.g.* for ^{266}Hs, or even double-humped [13], *e.g.* for ^{286}(112), all result from the barrier-free fission, but that the limits of these distributions remain those predicted by the nucleon phase, if the broadening due to the uncertainty on the mass is taken into account.



◀ **FIG. 2:** Description of the symmetric fission of ^{258}Fm in the nucleon-phase model by the sharing-out of 6, *i.e* of $(A_{cl}$ - 44), valence nucleons between the nucleon cores.

▲ **FIG. 3:** Discovery of the barrier- free fission of ^{258}Fm into ^{128}Sn + ^{130}Sn (ref.11).



The best argument in favor of the new definition of the fission barrier B^f as being the corrected external barrier B_C^f of the most energy-rich fragment pair, is that it explains why almost all actinide nuclei have B^f - values of ~ 6 MeV. Indeed, this pair always contains a tin nucleus or another "spherical" nucleus and has an almost constant ($B_C^{f corr.}$ - Q)-value. For example, the external fission barrier of ^{235}U + n_{th}, which corresponds to the most energy-rich pair ^{132}Sn -^{104}Mo, is positive and equal to 2.73 MeV. But after a plausible sphericity correction of ~ 3 MeV, it becomes equal to the quite commonly accepted B^f value of 5.80 MeV.

The symmetric fission mode, observed in ^{258}Fm and in heavier spontaneously fissioning nuclei, and which results from the laws of the nucleon phase, has to be distinguished from the phenomenon of appearance of an increased yield at symmetry observed in asymmetrically fissioning systems at higher energies. Ythier *et al.* have interpreted this situation as resulting from a kind of hindered barrier-free fission: the increase of E_{exc} in the expression of the fission barrier

$$B_f = B_C^{f corr.}(i) - [Q_{tot}(i) + E_{exc}] \qquad (2)$$

diminishes the still positive value of B^f, and makes the emission (by tunnel effect) of the most energy-rich pairs easier. However, the latter are precisely those having mass numbers close to $A_F/2$; hence the increased yield at symmetry.

The end of the nucleon phase

VI-a The nucleon-phase hypothesis raises a number of interesting questions. It may be asked what happens to the quarks as the distinction between proton and neutron disappears. It may especially be asked what happens at the end of this phase, and whether the appearance of phenomena related to the double giant dipole resonance could be the last expression of this nucleon phase.

VI-b In 1996, Mouze made the observation that the "missing energy" necessary for explaining the emission of alpha particles and other low-energy light charged particles could be furnished by the double giant dipole resonance (DGDR). Indeed, their maximal energy corresponds to the DGDR-energy minus the binding energy of the ternary particle [14]. And the DGDR-energy is large enough for setting free a small number of prompt neutrons from the valence shells of the A = 82 and A = 126 nucleon cores, for example the 3.76 prompt neutrons emitted on average by a ^{252}Cf nucleus, having a DGDR-energy of 26.4 MeV [1].

I thought it would be important to bring to light the quite novel ideas of Ythier and his coworkers on the mechanism of binary fission. Their description of this reaction might appear too daring, because it clearly rejects a number of widely accepted concepts.

However, their description is not only the outcome of a tenacious reflection conducted step by step in the last twenty years, it is also now a coherent representation, since *the nucleon-phase hypothesis provides a joint explanation of the most enigmatic experimental facts of binary fission, those revealed* by A.C. Wahl, by K.F. Flynn and L.E. Glendenin, by C. Signarbieux, by J. Terrell, by D.C. Hoffman, by E.K. Hulet and by M.G. Itkis. ■

About the Author

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note

[1] It was not possible to take into account here the work devoted by Ythier and Mouze (at times in collaboration with me) [15] to the various kinds of ternary fission and to their competition with cluster-radioactivity; the study of their relation to the nucleon–phase hypothesis is not completed yet.