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Publication Date

1971-12-01

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Presented at Ebeltoft Conference,
Ebeltoft, Denmark, May 19, 1971

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W. J. Swiatecki

December 2, 1971

AEC Contract No. W-7405-eng-48

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FISSION AND FUSION DYNAMICS. I*†

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December 2, 1971

I would like to say a few simple things about the combined field of fission and heavy ion fusion. I believe that fission and heavy ion fusion should be discussed in a unified way. In both cases one has to deal with drastic rearrangements of nuclear structures, where many nucleons are involved. One is dealing with a situation where, for many purposes, a macroscopic approach is expected to be a good starting point. A kind of nuclear macro-physics, characterized by $A \gg 1$, is what one wants to explore.

The characteristic feature of a macroscopic approach is that collective rather than single-particle degrees of freedom become convenient and relevant. Of course the microscopic approach always remains the more fundamental one and has to be used to answer fundamental questions. But the macroscopic approach becomes a convenient technique for treating many phenomena.

In virtue of the relative thinness of the nuclear surface (the "leptodermous" character of nuclei), the shape of the nuclear

* Work done under auspices of the U.S. Atomic Energy Commission.

† Based on a talk given at the Ebeltoft Conference, May 19, 1971, at Ebeltoft, Denmark.

surface is the relevant degree of freedom in a macroscopic description of fission and fusion.

In general many degrees of freedom are needed to specify accurately the shape of a dividing or fusing nucleus. If one is clever in one's choice of degrees of freedom this number may be reduced to a manageable set. I believe three degrees of freedom is the barest minimum necessary to display the essential features of fission and fusion dynamics.

These degrees of freedom are something like this:

1. An elongation coordinate, say $\tilde{\alpha}_2$.
2. A necking coordinate, say $\tilde{\alpha}_4$.
3. A mass-asymmetry coordinate, say $\tilde{\alpha}_3$.

(We use tildes over $\alpha_2, \alpha_3, \alpha_4$ to imply that these variables are only vaguely related to the coefficients of P_2, P_3, P_4 in an expansion of the nuclear shape in Legendre Polynomials. Having made this point we drop the tildes in the rest of the paper.) The nuclear shapes corresponding to these degrees of freedom can be displayed in a three-dimensional space like Fig. 1.

The fission of a nucleus would be described by some path in this configuration space, starting from the sphere and going somewhere to the right. Similarly, fusion would be another path, very roughly the reverse of fission. If we treat the problem quantum mechanically, we shall be solving a Schrödinger equation in the $\alpha_2\alpha_3\alpha_4$ space. In order to construct a dynamical theory of such paths or to solve the Schrödinger equation, we will need information about certain crucial properties of the nuclear systems considered. So before plunging into the discussion of the fission and fusion paths or of the wave functions

$\psi(\alpha_2\alpha_3\alpha_4)$, let us stop to ask what really are the crucial pieces of information that we will need in order to set up a dynamical theory of fission and fusion.

Well, <u>any</u> theory in applied physics may be said, since the time of Newton, to be based on <u>Equations of Motion</u>. This is true both in classical and quantum mechanics. Now, in general, there are three types of terms in an equation of motion:

	Associated with time derivatives	Relevant Quantities
1. Potential Energy Terms	ZEROTH	$V(\alpha_2\alpha_3\alpha_4..)$
2. Friction, Damping or Dissipative Terms	FIRST	Rayleigh's Dissipation Function or $iW(\alpha_2\alpha_3\alpha_4..)$
3. Inertial Terms	SECOND	$M_{\alpha_i\alpha_j}(\alpha_2\alpha_3\alpha_4..)$

The number <u>three</u> is no accident: it is associated with the fact that equations of motion contain zeroth, first and second time derivatives of the degrees of freedom, but no higher.

In classical mechanics the dissipative terms may be described by something called the Rayleigh dissipation function. In quantum mechanics the potential energy and the damping terms are sometimes combined in a complex potential $V(\alpha_2\alpha_3\alpha_4) + iW(\alpha_2\alpha_3\alpha_4)$. The inertial terms in classical as well as quantum mechanics give rise to a so-called inertia matrix or tensor $M_{\alpha_i\alpha_j}(\alpha_2\alpha_3\alpha_4..)$, which describes the inertial response of the system to changes in the degrees of freedom. In any case, there are three pieces of physics to consider in making a dynamical theory:

1. Potential Energy
2. Damping
3. Inertia.

In the case of nuclear macro-physics the situation today is that we have a good understanding of 1, a little of 3, and very little of 2. I believe that in the future we will have to concentrate on pulling up the information on Inertia and Damping to a level that matches our understanding of the Potential Energy.

In Szymański's talk we heard about the progress made in calculations of inertia coefficients. Sven Bjørnholm will describe some first steps in orienting ourselves with regard to the magnitude of damping terms. I will talk mostly about the Potential Energy, with some notions about inertia coefficients slipped in behind your backs.

Our understanding of the nuclear potential energy has made great progress in the last few years, principally as a result of the success of Strutinsky's prescription for combining macrosocpic and microscopic theories. We are today in a position where we can calculate the potential energy of a nucleus as a function of N,Z and the nuclear shape, with an accuracy of about ± 1 MeV. This is one MeV out of a total binding energy of some 2000 MeV.

What have we learned? The potential energy as a function of $\alpha_2\alpha_3\alpha_4$ is given by a pock-marked surface, consisting of a smooth part and shell effect pock-marks. The characteristic undulations of the smooth part are generally of the order of tens of MeV, the pock-marks are of the order of a few MeV. The theory underlying the smooth part is well understood. The pock-marks, though not so well understood, are also beginning to be related to simple features of the nuclear shape.

There is, or course, a wealth of structure in the problem, especially in the pock-marks. I could not possibly describe in a few minutes even the small part of the structure that I understand. All I will do today is to mention what I consider are the most important features of the smooth structure. (It will be like describing a porcupine as a prolate spheroid, which could be embarrassing, or like describing the earth as an oblate spheroid, which is pretty accurate. The accuracy of describing the nuclear potential energy by means of the smooth structure is better than for porcupines and worse than for the earth.)

There are two really fundamental properties of the smooth part of the potential energy maps. The first has to do with the mass-asymmetry coordinate, the second with a mis-alignment of certain potential energy valleys.

1. Existence of a Critical Mass Asymmetry
2. Existence of two Misaligned Valleys.

Critical Asymmetry

As regards assymetry the most important thing to keep in mind is that there exists a critical mass asymmetry, a critical ratio of masses of target and projectile. For mass asymmetries more extreme than the critical (i.e., for a light heavy ion) the target nucleus tends to suck up the projectile. For asymmetries less extreme than the critical (i.e., for really massive heavy ions), the projectile tends to suck up the target (until the two have become equal). Most heavy-ion experiments done to date lie on one side of the critical asymmetry. Most heavy ion experiments of the future (in particular those aiming at super-heavy nuclei) will lie on the other side of the critical asymmetry. The critical asymmetry is therefore an important feature

to bear in mind when extrapolating from past experience to future experiments with really heavy ions. (More about this in W. J. Swiatecki, UCRL-19405 and Proc. of Int. Conf. on Nuclear Reactions Induced by Heavy Ions, Heidelberg, July 15-18, 1969.) (An example of a system with critical asymmetry is a neon ion and a heavy nucleus in contact.)

Misaligned Valleys

The second important feature of the Nuclear Potential Energy maps in $\alpha_2\alpha_3\alpha_4$ space is the existence of two valleys, similarly oriented but mis-aligned. Let me explain. Think now of a fixed mass-asymmetry, i.e., a section through the $\alpha_2\alpha_3\alpha_4$ space along a fixed α_3. The nuclear shapes as functions of α_2 and α_4 are shown in Fig. 2.

The simplest way to summarize the findings of many people who have investigated the potential energy in spaces like the $\alpha_2\alpha_4$ space is to say that there are two valleys, as shown. One valley starts from the vicinity of the sphere. After a saddle, the energy goes down, but there is stability against changes of the necking coordinate for a fixed elongation coordinate. Below this valley is a roughly parallel Two-fragment valley corresponding to approaching or separating fragments.

(Farther up there is a third valley, the Three-Fragment Valley, about which I will not say anything more.)

How do the valleys fit together? I have shown an oversimplified sketch to give you a hint of what the situation looks like. A plan, an end view and a side view of the potential energy surface as function of α_2 and α_4. (See Fig. 3.)

I hope you can see the fission valley with its saddle and stable spherical shape and the misaligned two-fragment valley. Between the two is a ridge running from A to C. Remember also that on top of what I described are shell-effect pock-marks. (One of these is shown: the magic hole H, responsible for the stability of a super-heavy nucleus.)

With this potential energy surface as background we can now sketch in a fission path corresponding to a dividing system. The nucleus deforms, goes over the saddle and rolls down the fission valley. In the neighborhood of point C equilibrium against necking in is lost and the system is injected into the two-fragment valley. Because of the misalignment of the valleys the injection is off-axis and the representative point vibrates around the axis as it descends the two-fragment valley. This vibration corresponds to changes in eccentricity of the fragments i.e., to fragment excitation. The excitation energy is roughly the difference in energy between points C and D. Experimentally it is typically 20 - 40 MeV and is eventually dissipated in neutron evaporation from the fission fragments.

Now about fusion. The situation is analogous. We proceed up the Two Fragment Valley corresponding to approaching nuclei. At the point A, corresponding to tangency, equilibrium against an increasing eccentricity of the fragments is lost and the system is injected into the fission valley. Because of the off-center injection there is vibration about the axis of the fission valley, which would eventually lead to excitation of the fused system. The amount of excitation is roughly the difference between the energy at A and at B.

An analogy to these fission and fusion paths may be constructed in terms of the path of a beam particle in a linear accelerator. (This seems appropriate at an accelerator conference.) Imagine a linear accelerator consisting of two misaligned segments. Each segment has radial focusing (e.g., quadrupole lenses). A short pre-accelerator

(the fission valley) injects a particle into the main accelerating tube, which, however, is misaligned. Conversely, in fusion, a particle is sent back up the main accelerator and is then injected up-hill into the pre-accelerator. Because of the misalignment, transverse oscillations are set up in the beam at injection. These oscillations correspond to fission fragment excitations in the case of fission, or to the excitation of the fused nucleus in the case of fusion.

The question of estimating the amount of excitation following a fusion reaction is one of the outstanding problems in trying to make super-heavy nuclei. (If there is too much excitation one will not be able to make them.) I am currently trying to apply the picture of the two misaligned valleys to estimate this excitation in the case of heavy ion reactions.

From other considerations I believe there are actually rather few combinations of target and projectile that one should concentrate on:

1. $Th^{232} + Ge^{76}$ (8% abundance of projectile isotope)
2. $U^{238} + Ni^{64}$ (1% abundance of projectile isotope)
3. $Cm^{248} + Ca^{48}$ ($\frac{1}{5}$% abundance of projectile isotope) .

In the first of these my estimates of the energy difference between A and B went something like this. If, in making the potential energy maps, one forgets about the diffuseness of the nuclear surface and the finite range of nuclear forces, one gets

$$E_A - E_B \approx 80 \text{ MeV} .$$

If one allows for the diffuseness of the nuclear surface and the finite range of nuclear forces the energy difference $E_A - E_B$ appears to go down to something like 40 MeV. This is because the nuclear interactions help to lower the two-fragment valley in the vicinity of the point A. Then a further nice thing happened. If one allows for the ground state deformation of the Th^{232} target, and one considers reactions where the Th^{232} is hit on the nose (rather than broadside) then the energy difference E_{AB} goes down further to something like 20 MeV. This is again because with an elongated target the nuclear interactions can "reach out" and lower the energy of the point A. With such a low nuclear excitation, my own excitation went up very steeply. With only 20 or 30 MeV excitation in the compound nucleus one begins to dream of cross-sections for the formation of super-heavy nuclei in the range of $10^{-28} - 10^{-29}$ cm^2. One might one day be making weighable amounts of the new elements.

Then Sven Bjørnholm comes along and starts talking about large damping effects in fission, i.e., large frictional effects acting on the ball that is rolling around on the potential energy surface. (This is like having a poor vacuum system in the accelerator. The vibrating particles in the beam get slowed down and are eventually lost.) This damping, if large, would damp my excitation considerably. You can probably see at once that too much friction will make fusion very difficult if not impossible. This is because the point B is still some 10 or 15 MeV below the saddle that must be overcome in order to enter the magic hole H. One hopes to provide this extra energy by increasing the bombarding energy by 10 or 15 MeV over the Coulomb barrier. But if there are large frictional losses, only a fraction of the excess bombarding energy will go into the collective degree of

freedom leading from B to S, and the rest of the energy will go into heat (excitation). If too much goes into heat and too little into collective motion, then one can say goodbye to super-heavy elements. So the question of damping or friction appears to be quite critical.

Let me summarize the main points of my talk:

1. Fission and Heavy Ion Fusion are parts of a single field of nuclear macro-physics.

2. There are three pieces of physics one has to know to discuss this field: Potential Energy, Damping, Inertia.

3. In the smooth part of the Potential Energy the main features are a <u>critical mass asymmetry</u> and <u>misaligned valleys</u>.

4. The prospects for super-heavy nuclei look reasonably good unless damping is too large.

Now let us see what Sven Bjørnholm can say about the damping.

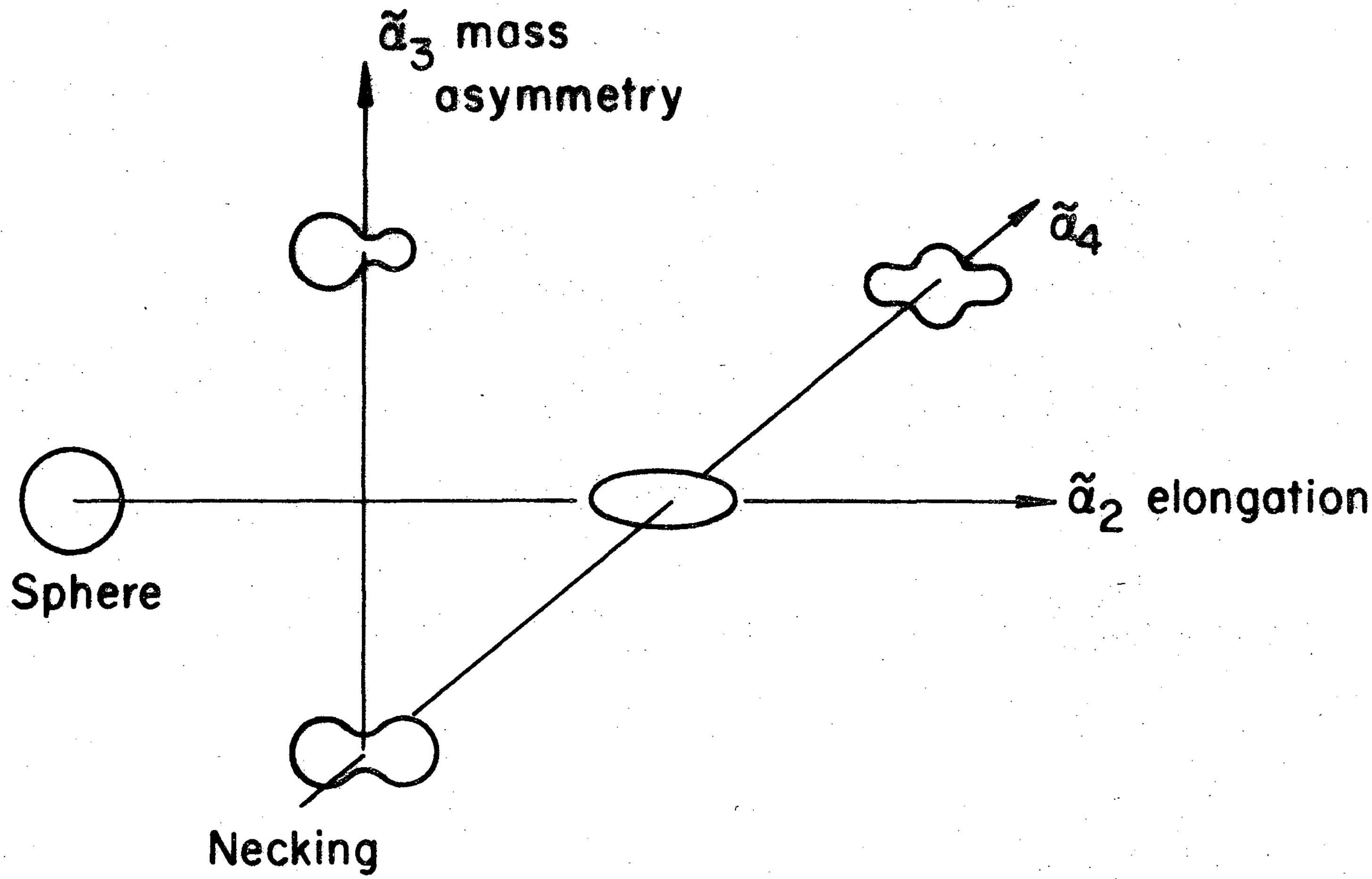

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Fig. 1

0 0 0 0 3 7 0 4 8 1 4

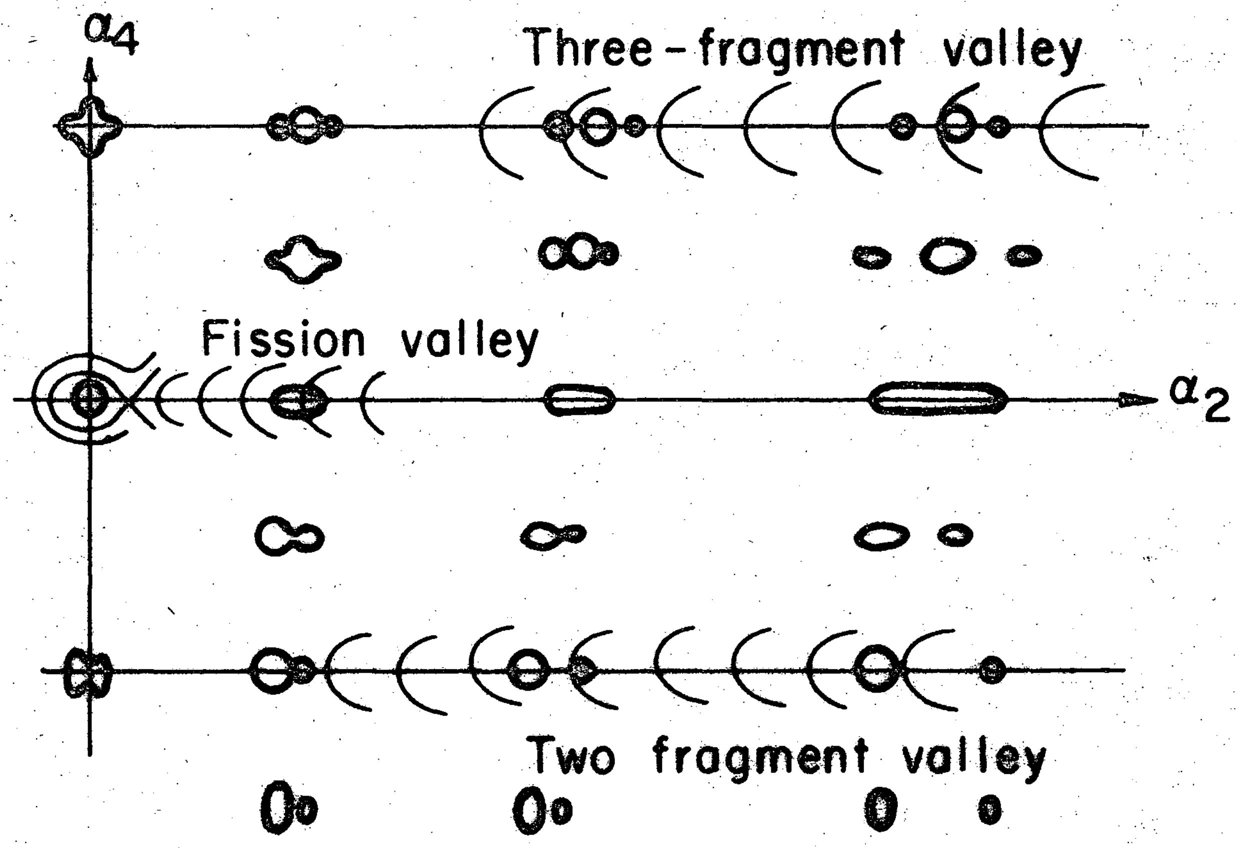
Three-fragment valley
Fission valley
Two fragment valley
α_4
α_2
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Fig. 2

0 0 0 0 0 7 0 4 8 1 5

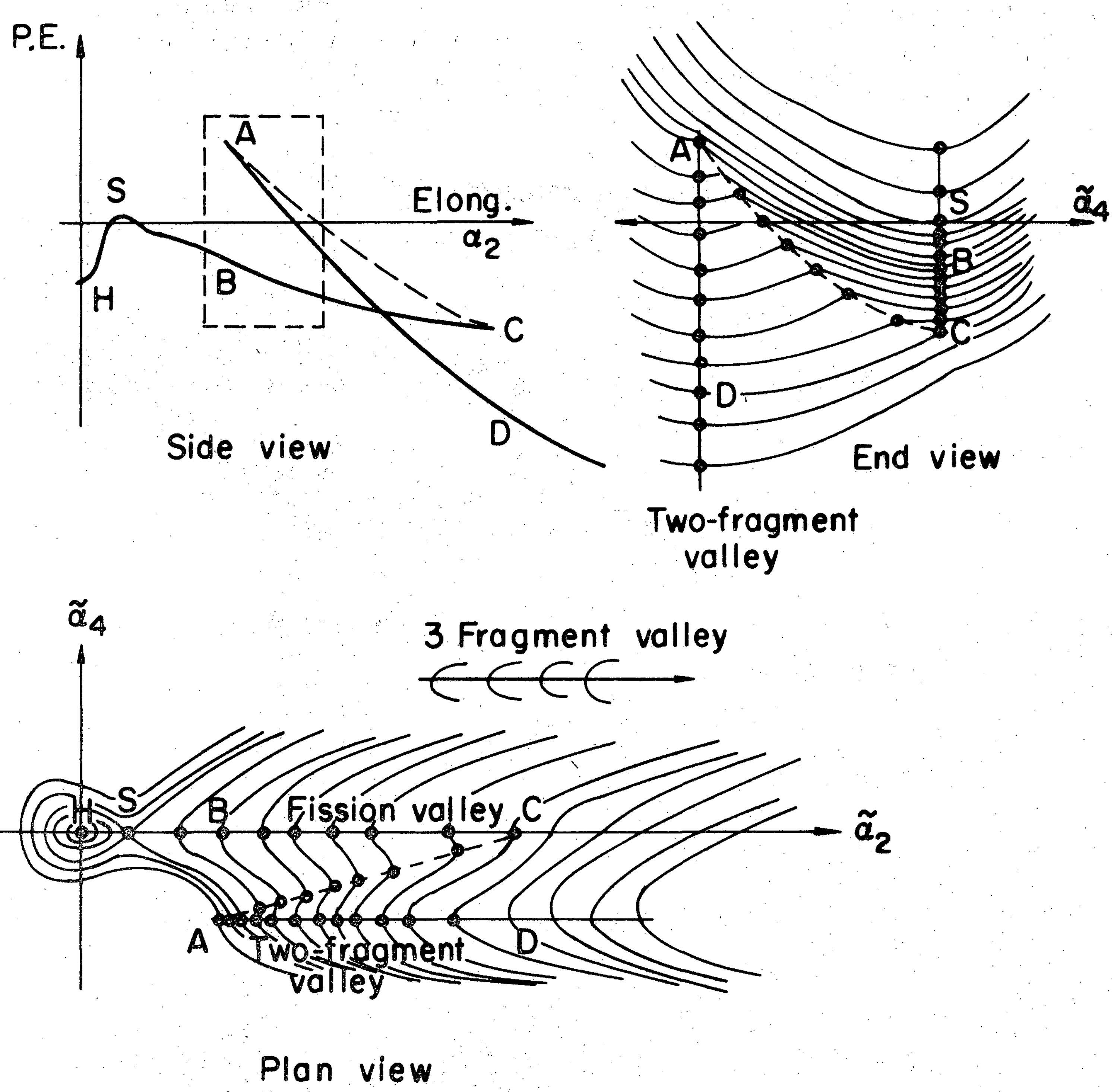

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Fig. 3

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