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ON A NEW TYPE OF FISSION-ISOMERIC STATE

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A study of the relevant single-particle diagram reveals the presence of a unique neutron orbital [505$\frac{11}{2}$] which for $N \approx 144$-150 passes through the Fermi surface for the distortion shapes characteristic of the fission-shape-isomeric state. This orbital gives rise to a specialisation energy in excess of 4 MeV for the second barrier peak. This energy increment is in turn expected to be associated with an increase in the half-life of the "normal" fission-shape-isomer by a factor of about 10^{15}. Recent experimental findings of an 0.3 year isomer in ^{241}Pu is explained in terms of the specialisation energy connected with this orbital.

The phenomenon of fission isomerism [1,2] associated with half-lives of the order of micoseconds has been explained on the basis of the occurence of secondary minima in the potential-energy surface. These in turn have been shown to be associated with shell-structure effects [3-9]. It was suggested at an early stage that some isomeric behaviour might be due to the exceptional specialisation energy (a concept introduced by Wheeler [10]) associated with certain high-angular momentum single-particle orbitals. It is contended that a uniquely favourable case involving both shape isomerism and specialization energy may in the actinide region be associated with the particular neutron orbital [505 $\frac{11}{2}$] and on the proton side possibly the proton orbital [404$\frac{9}{2}$] or, less favourably, [514$\frac{9}{2}$]. In particular this first orbital happens to pass through the Fermi surface, for the distortion associated with the shape isomeric state, for neutron numbers between $N = 142$-148. We believe this coincidence to be the explanation of the recently encountered 0.3 year half-life of a ^{241}Pu isomer discussed in ref. 11 and a forthcoming paper [12].

The calculation of the single-particle structure and the total potential-energy surface is based on the potential of refs 4,7 and 8

$$V = \tfrac{1}{2}\hbar\omega_0(\epsilon,\epsilon_4)\,\rho^2(1 - \tfrac{2}{3}\epsilon P_2 + 2\epsilon_4 P_4) + \\ - \kappa\hbar\mathring{\omega}_0\,[2\,\boldsymbol{l}_t\cdot \boldsymbol{s} + \mu(\boldsymbol{l}_t^2 - \langle \boldsymbol{l}_t^2\rangle_N)]$$

which potential is further discussed in refs. 4,7 and 8. With the help of only the two parameters, κ and μ, this potential is capable of reproducing accurately the observed single-particle level order for the ground-state equilibrium shapes, as is well known.

In the region centered around $A \approx 242$ we have employed $\kappa = 0.0635$, $\mu = 0.325$ for neutrons, and $\kappa = 0.0577$, $\mu = 0.650$ for protons. The single-particle energies corresponding to this potential are computed for a set of grid points in the (ϵ, ϵ_4) plane. Occupied orbitals are subsequently summed over to obtain the total-energy surface. The summation prescription is adequate provided the condition of volume conservation (with inclusion of the P_4 term) is observed and, in addition, the Strutinsky [3] normalisation is applied, whereby the averaged behaviour is normalized to that of the liquid-drop model. In this normalized sum a Coulomb and a surface energy term (computed without resort to expansions) are included. The pairing correlation energy is furthermore computed on the basis of a surface and isospin dependent pairing matrix element and subsequently added, apart from an averaged contribution. Details of the compution are found in ref. 8. In the total-energy surface for the even-even case two relevant minima are encountered in this region of nuclei. The first, and usually the lowest, minimum is associated with shapes with $\epsilon \approx 0.25$. The secondary minimum, encountered for the even-even case in this region of nuclei, is associated with distortion coordinates $\epsilon \approx 0.6$-0.7 and $\epsilon_4 \approx 0.04$ - 0.10. (A slight waistline, $\epsilon_4 > 0$, is thus developed relative to the pure spheroid.)

In fig. 1 we may study the single-particle level scheme associated with the shape isomeric distortions. Fig. 1 represents a cut in the (ϵ, ϵ_4) plane roughly along the fission path, which is somewhat different for different nuclei.

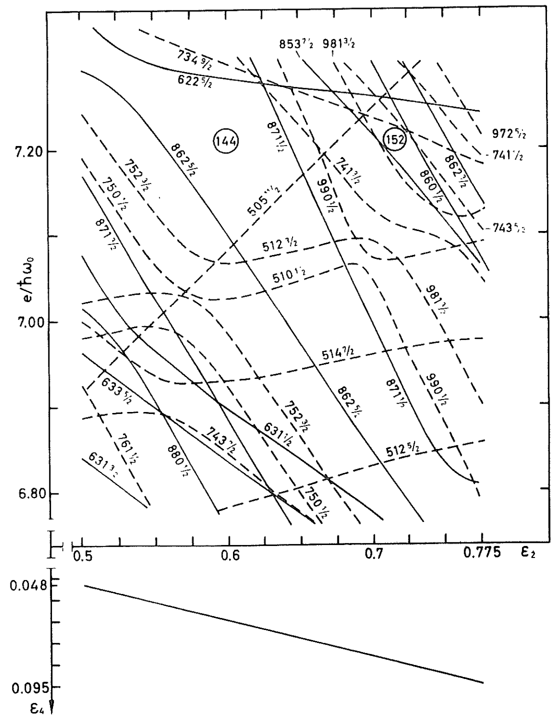

Fig. 1. Neutron orbitals for $A \approx 242$ along parts of an averaged "fission path" in the (ϵ, ϵ_4) plane [13]. (The location of the "path" is indicated at the bottom of the diagram.) Orbitals are assigned "asymptotic" quantum-numbers.

Curves of the same Ω-value and parity approach each other to within the strength of the coupling term $\rho^2 P_4$. One should note that the orbital $[505\,\frac{11}{2}]$ approaches no other $\frac{11}{2}^-$-states for large areas beyond the area of distortion covered by the diagram. Indeed there is *no* $\frac{11}{2}$-state *below* $[505\,\frac{11}{2}]$ and the nearest one above, $[725\,\frac{11}{2}]$, is almost one oscillator shell $\hbar\omega$ above for the shape isomeric distortion and exhibits a variation with ϵ not much different from that of $[505\frac{11}{2}]$. The $[505\frac{11}{2}]$ orbital is found to cross the Fermi surface for $N \simeq 147$ at $\epsilon \simeq 0.67$, which is very near the even-even secondary minimum.

In the odd-A case the (interpolated) even-even energy is to be incremented by the quasi-particle energy term. The latter represents the energy modification associated with the odd-particle orbital. For a particular orbital ν, the well known quasi-particle energy expression is the following

$$E_\nu = \sqrt{(\epsilon_\nu - \lambda)^2 + \Delta^2}$$

where λ is the Fermi energy and Δ the gap parameter.

A computer program has been constructed that computes the total potential-energy surface for such an odd-A system with the odd particle placed in an orbital of given angular momentum component Ω and parity Π and minimal E_ν.

The relevance of an energy surface for the odd-A system, computed according to this recipee, rests, of course, on the correctness of the assumption that not only is the total angular momentum component K preserved but, throughout the barrier penetration, it remains centered on a single orbital with $\Omega = K$. (Only one-quasi-particle states are thus considered.) On the other hand it is assumed that the odd particle may switch to another orbital of the same Ω and Π once the alternative orbital comes nearer to the Fermi surface, λ.

Fig. 2 exhibits a cut in the (ϵ, ϵ_4) plane for ^{241}Pu such that for each ϵ the ϵ_4 value is selected that gives minimum energy. In this figure we give firstly the even-even barriers (dashed lines), secondly the $[\frac{11}{2}^-]$ isomeric barrier shapes (solid lines), and for comparison (long-dashed,

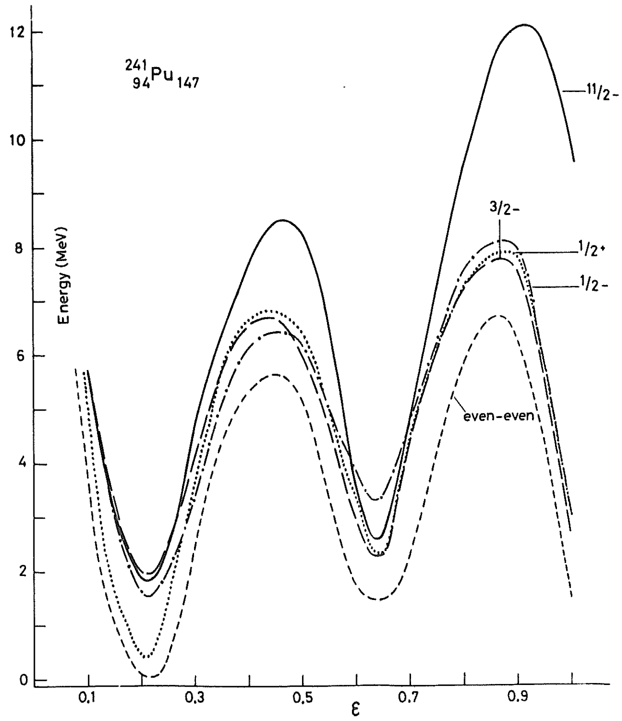

Fig. 2. Cuts through the energy surfaces corresponding to an "even" ^{241}Pu nucleus (dashed) (interpolated between ^{240}Pu and ^{242}Pu) and to minimum configurations with the odd-particle places in an optional $\frac{11}{2}^-$ (solid), $\frac{3}{2}^-$ (long-dashed), $\frac{1}{2}^+$ (dotted), and $\frac{1}{2}^-$ (dot-dashed) orbital.

dotted and dot-dashed) the low lying $[\frac{3}{2}^-]$, $[\frac{1}{2}^+]$ and $[\frac{1}{2}^-]$ barrier shapes.

It is clearly seen that the unique specialisation energy of the $[505\,\frac{11}{2}^-]$ orbital gives rise to an increase of the second barrier peak, by approximately 4 MeV.

In the ^{241}Pu case we have estimated the fission half-life as follows. As no calculations of the inertial parameter B exist for the odd-N case involving the unusual $[\frac{11}{2}]$-orbital, we have simply started from the averaged theoretical even-even inertia parameter [14] for the actinides of $B \approx 1000\ \hbar^2$ MeV. For the odd-N case calculations [15] give a value of about 1300 for $\epsilon \approx 0.5$, which is the characteristic increase of B in the odd-N case relative to that of the even-even one. With this value of B taken to be valid for both of the barriers we have calculated the WKB integral for the outer barriers of fig. 2. The orbital, theoretically associated with the lowest shape isomeric state, is found to correspond to a theoretical half-life of 10^{-6} sec. We assume this to be identified with the 3×10^{-8} sec isomer encountered earlier for ^{241}Pu. The $[505\,\frac{11}{2}]$-orbital is associated with a half-life theoretically about 10^{15} times longer, i.e. of the order of months. Provided $K = \frac{11}{2}$ empirically becomes the lowest-lying orbital in the secondary minimum, a very long half-life is highly probable. If the $[505\,\frac{11}{2}]$ is a low-lying excited state, its gamma decay is expected to be highly hindered either due to high ΔL or high ΔK-values. One must, of course, here point out that the theory is hardly accurate enough to predict the exact level ordering within an energy of a few hundred keV.

In assessment of the half-life estimate some of the uncertainties should probably be emphasized. In particular the height of the second barrier peak probably represent somewhat of an overestimate, as e.g. three-quasi-particle states of given spin and parity might be available at a lower energy than the one-quasi-particle excitation. In the half-life estimate with respect to the second barrier, this error is probably in part compensated by the employment of an inertial-mass parameter value averaged for the entire barrier.

The competing process of gamma decay back through the inner barrier is expected to be sufficiently delayed (as the normal gamma width is to be multiplied by the small penetration factor) so as not to seriously affect the preponderance of the fission process.

Actually also the height of the first peak is probably underestimated compared with that of the second one for the following reason:
The odd-particle is associated with the orbital $[505\,\frac{11}{2}]$ at the isomeric minimum and remains in this orbital through the outer barrier.
For the inner barrier, on the other hand, it becomes energetically more favourable for distortions less than $\epsilon \approx 0.5$ to associate the odd particle with $[725\,\frac{11}{2}]$. This transition from a hole to a particle orbital, assumed entirely effective in the calculations, may be expected to be less efficiently realized in the real nucleus. Thus for a large fraction of the time the system may remain associated with the $[505\,\frac{11}{2}]$ hole state. This effectively corresponds to a larger inner barrier.

The experimental finding [11] of a 0.3 years fission isomer in the ^{241}Pu nucleus makes it highly probable that, for the shape isomeric distortion, the $[505\,\frac{11}{2}]$ orbital is indeed the $N = 147$ orbital. The finding gives a very firm support to the belief that *we indeed know where* in the single-particle level diagram *the shape isomers occur.* It also gives an unexpected support to the capability for extrapolation to larger distortion inherent in the remarkly simple modified oscillator potential.

The ultimate confirmation of the explanation here suggested would probably be provided by a direct measurement of the isomeric spin. For the long half-lives here in question such a measurement should be technically possible.

More complete calculations are forthcoming and will be published elsewhere by one of us (G.O.).

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