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SCHEMATIC MODEL OF TWO HARD CORES FOR COLD FISSION(1)

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ABSTRACT

Structures in mass and total kinetic energy distribution (TKE) in cold fission of ^{234}U, ^{236}U, and ^{240}Pu are interpreted in terms of a static scission configuration model. The role of shells in fragments present in their deformation energy function, in the Coulomb interaction energy between fragments at scission (C), and in the available energy (Q) are studied in detail. The maximal value of C, C_{max}, correspondig to the most compact scission configuration, is calculated for several mass fragmentations. It is shown for a given primary fragmentation and Q being constant, that, if one increases the charge asymmetry, C_{max} will increase. This dependence produces oscillations of C_{max} as a function of light fragment mass (A_L) wich are correlated with the observed oscillations of the maximal values of TKE, TKE_{max}. The calculated C_{max} values show odd-even effects in contrary to the experimental smooth TKE_{max} -lines. A schematic approach, in terms of two hard cores and a certain number of orbiting nucleons during the process of fission, is used to calculated odd-even effects in proton and neutron number distributions and in the fragment kinetic energy as a function of fragment charge. One assumes that pair breaking occurs between saddle and scission. A small fraction of total fission events ends up in paired states in both fragments.

RESUMEN

Las estructuras en la distribución de masa y energía cinética total (TKE) en la fisión fría de ^{234}U, ^{236}U y ^{240}Pu son interpretadas en términos de un modelo de configuración estática. Se estudia en detalle el rol de las capas en los fragmentos presentes en la función de su energía de deformación, en la energía de interacción coulombiana entre los fragmentos de fisión, y en la energía disponible (Q). El valor máximo de C, C_{max}, correspondiente a la configuración más compacta, es calculada para varias fragmentaciones de masa. Se muestra, para una fragmentación primaria dada y un valor constante de Q, que, si se aumenta la asimetría de carga, C_{max} aumentará. Esta dependencia produce oscilaciones de C_{max} como una función de la masa del fragmento liviano (A_L) la cual está correlacionada con las oscilaciones observadas en el valor máximo de TKE, TKE_{max}. Los valores calculados C_{max} muestran efectos par-impar en constraste a los valores experimentales de las líneas suaves TKE_{max}. Un modelo esque-

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mático, en términos de dos núcleos duros y un cierto número de nucleones orbitantes durante el proceso de fisión, es usado para calcular efectos par-impar en la distribución de número de protones y número de neutrones y en los valores de energía cinética como una función de la carga de los fragmentos. Se asume que la ruptura de parejas ocurre entre el punto de ensilladura y la escisión. Una pequeña fracción del total de eventos de fisión terminan emparejados en ambos fragmentos.

1. INTRODUCTION

The structure of the fragment mass and charge distribution in low energy fission of heavy nuclei was interpreted as a function of pairing and shell effects [1]. In the case of ^{234}U, ^{236}U, and ^{240}Pu, produced by the capture of thermal neutron by ^{233}U, ^{235}U, and ^{239}Pu, respectively, those structures are more pronounced in high windows of light fragment kinetic energy, E_L [1]. This result promoted the measurement of charge, mass, and kinetic energy in regions with small excitation energy of the fragments, that is as close as possible to the region of cold fission, defined as fission with no neutron emission. The system ^{234}U, ^{236}U, and ^{240}Pu were the most studied in the region of cold fission. The "Lohengrin" recoil separator had permitted, to several authors [2-5], to measure the flight fragment kinetic energy, E_L, the light fragment mass A_L, in windows of light fragment kinetic energy, E_L. A time-of-flight method has been used by other authors [6,7] to measure the total kinetic energy (TKE) and fragment mass distribution for the mentioned fissionable systems. From this distribution the maximal value of TKE, TKE_{max}, as a function of A_L has been estimated. A recent review is given in Ref. [8].

The purpose of this paper is to analyze the influence of i) the shell effects reflected in the deformability properties, ii) the Coulomb effect defined as the increase of TKE_{max} observed for a given fragmentation where for cases of equal Q-values the charge asymmetry increases, iii) the available energy, Q, and iv) the nucleon pair breaking in the fragment charge, mass, and kinetic energy distribution in the region of cold fission. The analysis allows to understand the surviving charge in the region of the highest values of total kinetic energy.

The maximal value of the Coulomb interaction energy between the two fragments at the scission configuration, C_{max}, will be calculated by a static scission model and compared to the experimental values of TKE_{max}.

Finally, for the process of transition between saddle to scission a schematic model of two hard cores and orbiting nucleons is suggested, wich will permit to calculated the odd-even effects on fragment proton and neutron number distributions and of odd-even effects on fragment kinetic energy as a function of charge.

2. THE MOST COMPACT SCISSION CONFIGURATION

At the scission configuration the potential of two fragment system (P) is the sum of the total deformation energy (D) and the mutual Coulomb energy (C). The light and heavy fragments could have intrinsic excitation energy (X). In addition, the two fragments could have obtained a prescission kinetic energy (TKE_o). Using these definitions, the energy balance at the scission configuration gives the following equation:

$$Q = D + X + C + TKE_o, \quad (1)$$

where Q is the available energy for the fission process.

The most compact scission configuration corresponds, by definition, to the highest Coulomb interaction energy. It is assumed that this configuration is constituted by non-excited fragments, without prescission kinetic energy. Then, equation (1) will be reduced to :

$$Q = P_{max} = D + C, \qquad (2)$$

Notice that this configuration corresponds to the maximal value of the potential energy, which cannot be higher than the Q-value. From relation (2) we see that the highest possible value of mutual Coulomb energy C_{max} corresponds to the minimal possible deformation energy, D_{min}. In order to calculate the most compact scission configuration, the deformation energy and the Coulomb interaction energy as a function of the shape of the configuration is needed.

Let us assume there is a prescission kinetic energy TKE_0 which is not zero, see Fig. 1. Then, the maximal value of the potential energy P' for the most compact scission configuration will be smaller than for the case with $TKE_0 = 0$.

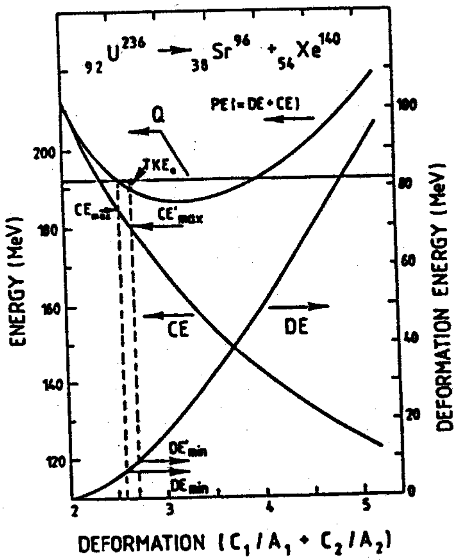

Fig. 1: Total fragment deformation energy (DE), Coulomb interaction energy (CE) of scission configurations limited by the total available energy (Q) for the fragmentation $^{96}_{38}Sr/^{140}_{54}Xe$ (from Ref. [1]) . If one assumes a prescission total kinetic energy (TKE_0), the most compact configuration will correspond to a total kinetic energy (TKE'_{max}) lower than TKE_{max}, obtained assuming a null precision total kinetic energy.

In the involved region of deformations the potential energy decreases with deformation. Let us take a schematic one dimensional function of the deformation energy and let us assume that this function increases with deformation. Then the deformation energy D' for $TKE_o \neq 0$ is larger that D for $TKE_o = 0$. The maximal value of the total kinetic energy, the sum of C and TKE_o equals the difference of the Q-value and the minimal value of the deformation energy. It follows a smaller value of the total kinetic energy TKE for the case $TKE_o \neq 0$ compared to $TKE_o = 0$.

2.1 COULOMB EFFECT

Let Z_L/Z_H and $(Z_L - 1)/(Z_H + 1)$ be two charge fragmentations for the same mass ratio A_L/A_H. Assuming the two corresponding scission configurations have the same deformation parameters, one gets the relation

$$\frac{C_{Z_L}}{C_{Z_L-1}} = \frac{Z_L Z_H}{(Z_L - 1)(Z_H + 1)} \qquad (3)$$

The Coulomb interaction energy at the most compact scission configuration amounts to about 200 MeV. For the difference $C_{Z_L} - C_{Z_L-1}$ a value of about 2 MeV is obtained. In Fig. 2

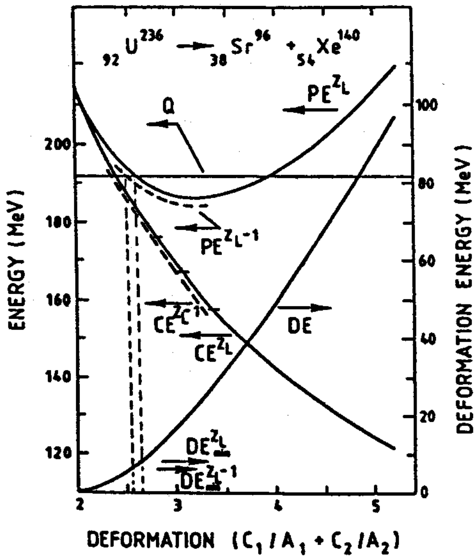

Fig. 2: Total deformation energy (DE), Coulomb interaction energy (CE) of scission configurations limited by the total available energy (Q) for fragmentation ${}^{96}_{38}Sr/{}^{140}_{54}Xe$ (from Ref. [1]). If one assumes a second charge fragmentation $(Z_L-1)/(Z_H+1) = 37/55$ having the same Q-value, one will obtain a total kinetic energy TKE^{Z_L-1}, higher than TKE^{Z_L}

the curves C, corresponding to Z_L and $(Z_L - 1)$, respectively, as a function of fragment deformation are schematically presented. Let us assume that the deformation energy function and the Q values are the same for the two charge fragmentations. It is easy to see that a smaller value of the deformation energy D_{min} and a larger value for the maximal total kinetic energy TKE_{max} correspond to the more asymmetrical charge fragmentation. This favouring of the higher values of TKE_{max} for the lower of two charge fragmentations of equal Q values for a given mass fragmentation will be called the Coulomb effect on TKE_{max}. The fragment deformability properties play an important role in the magnitude of the Coulomb effect. For instance, if the fragment deformation energy would not depend on the deformation in the domain of the most compact scission configuration, the TKE_{max} would be constant. This means that, if the fragments are very soft, the Coulomb effect will vanish.

2.2 SHELL AND PAIRING EFFECTS

In order to estimate the role played by the fragment deformation one can calculate for each fragment the deformation energy using the Strutinsky prescription [9]. The shell [10], U, and pairing [11], P terms are added to the liquid drop energy [12],W.

The relative variation of the deformation energy of a fragment is calculated by the difference.

$$D = (\widetilde{W} + \delta P_N + \delta U_Z + \delta P_Z) - \widetilde{W}_s; \qquad (4)$$

Where $\widetilde{W}$ and $\widetilde{W}_s$ are the smoothed values, corresponding to deformed and spherical shapes of the fragment, $\delta U_{N,Z}$ and $\delta P_{N,Z}$ are the shell and pairing terms corresponding to neutrons and protons, respectively.

In the Figs. 3a and 3b, δU_N and δP_N for Z=40 and N=58-62 are presented. One can see that δU_N and δP_N, in function of the Nilsson deformation parameter, ε, are anticorrelated. The curves δU_N for N=58-62 converge in $\varepsilon = 0.3$. There is a trend that values of δU_N for even N's are higher than the values corresponding to odd N's, in contrary to what happens with δP_N.

In Figs. 4a and 4b, δU_Z and δP_Z, respectively, for N=60 and Z=40-43 are presented. The δP_Z values corresponding to even Z's are lower than the values corresponding to odd Z's. The curves of δU_Z for Z=40-43 converge in $\varepsilon = 0.3$. In Fig. 5, the values for nuclei corresponding to Z =42 and N= 60 - 64, are presented. For N=60-63, in the deformation region ε =0-0.5 the curves approach a minimun for ε =0.25 and increase rapidly for higher deformations. The deformation energies of the light and heavy fragments are calculated relative to their ground state ($\varepsilon = \varepsilon_o$). They are obtained from the differences of the values at deformation ε and ε_o.

The maximal value of the Coulomb interaction energy at the scission configuration is calculated as the difference between the Q-value and the deformation energies of the fragments. In Fig. 6, equipotential energy curves, P, at scission configuration for the fragmentation $^{104}_{42}Mo/^{130}_{50}Sn$ are presented. The equi-Coulomb energy curves are parallels to the dashed one which corresponds to C = 204 MeV. The Q values [14] limit the deformation region of scission configurations. With Q = 204.4 MeV and D = 0.2 MeV one obtains C_{max} = 204.2 MeV, which is very close to the Q-value and corresponds to light and heavy fragments in their ground state, ($\varepsilon_L = 0.3$) and ($\varepsilon_H = 0$), respectively. Coulomb interaction energies very close to the Q values are obtained for fragmentations corresponding to light fragments Z_L=60. These fragments are deformed in their ground states. A different picture is obtained for the fragmen-

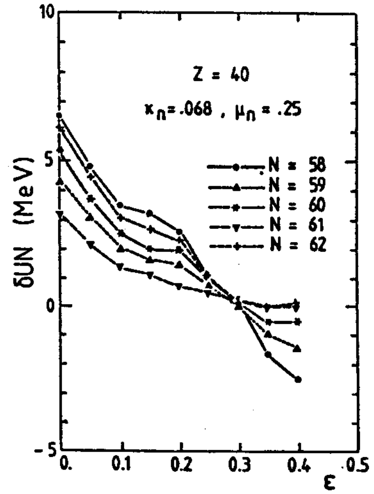

Fig. 3a: Neutron shell correction to the drop liquid energy corresponding to Z=40 and N= 58-62. κ_n=0.068 and μ_n=0.25 are the modified neutron spin-orbit correction terms [19].

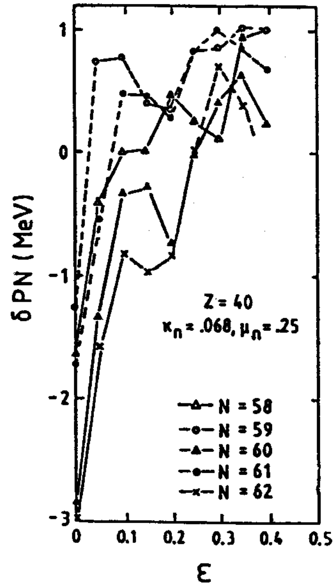

Fig. 3b: Neutron pairing correction corresponding to the cases presented in Fig. 3a.

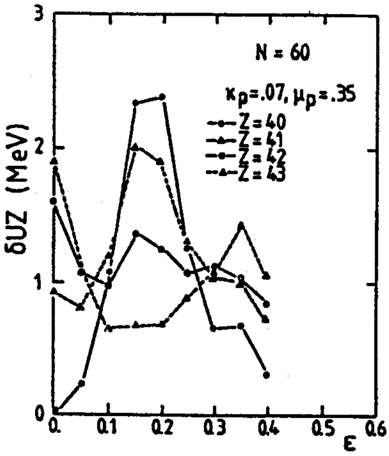

Fig. 4a: Proton shell correction to the liquid drop energy corresponding to N=60 and Z=40-43. κ_p=0.07 μ_p=0.35 are the modified proton spin orbit corrections terms [19].

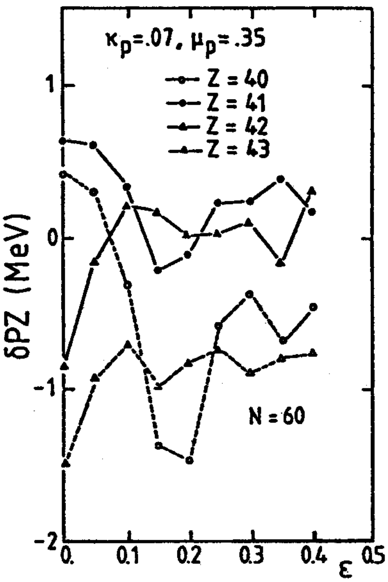

Fig. 4b: Proton pairing corrections corresponding to the presented in Fig. 4a.

tation $^{96}_{38}Sr/^{138}_{54}Xe$. In this case, Fig. 7, the maximal value if the Coulomb energy is C_{max}=196.5 MeV, while the Q value is Q =199.8 MeV giving a total deformation energy of 3.3 MeV. The corresponding configuration is a heavy fragment in its spherical shape and the light fragment with a deformation ε= 0.37

2.3 INFLUENCE OF THE Q-VALUE

The Q-value limits the domain of fragment deformations at the scission configurations, as one can see in the schematic figure 1. Let us take two charge fragmentations corresponding

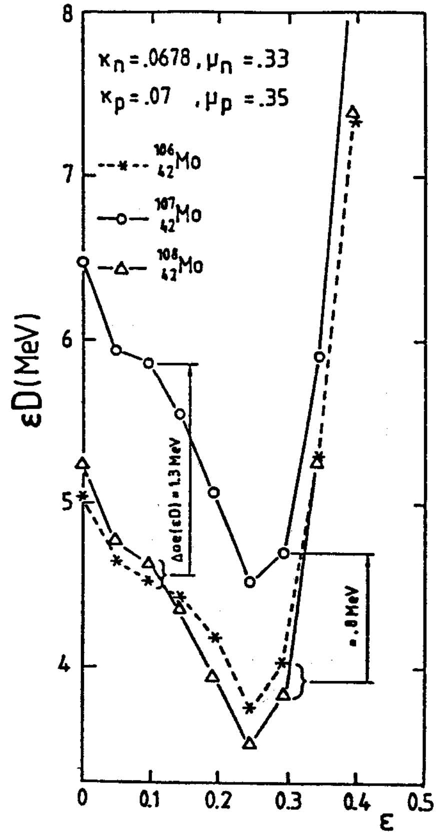

Fig. 5: Deformation energy (relative to the smooth value of energy of spherical state) of nuclei $^{106,107,108}Mo$ calculate with shell and pairing corrections. κ_n=0.0678, μ_n=0.38 are neutaron spin-orbit correcation terms and κ_p=0.07 and μ_p=0.36 are the proton spin-orbit correction terms [19].

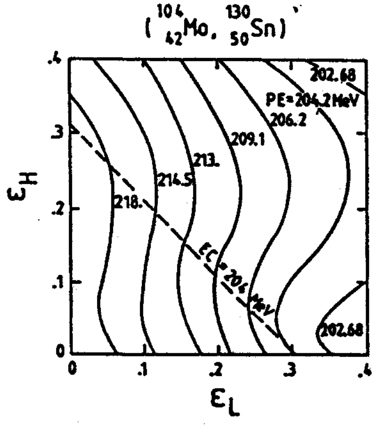

Fig. 6: Equipotential energy lines (—) in function of fragment deformation at scission configuration of fragmentation ${}^{104}_{42}Mo/{}^{130}_{50}Sn$. The fragment deformations are represented by the Nilsson parameters ε. The dashed line is the equi-Coulomb interaction emergy line corresponding to highest value permitted by the Q-value=204.2 MeV. The most compact configuration corresponds to ε_L=0.3 for ${}^{104}_{42}Mo$ and ε_H=.0 for ${}^{130}_{50}Sn$. Both fragments are in their corresponding ground state deformation. The fragment surfaces are fixed to 2fm.

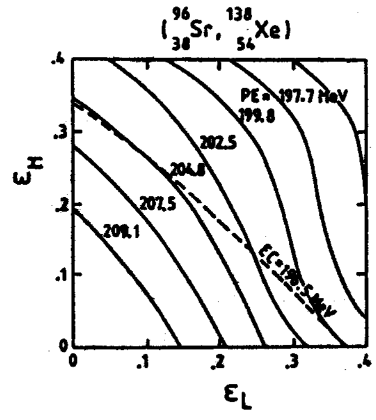

Fig. 7: Similar to Fig. 6 corresponding to the fragmentation ${}^{96}_{38}Sr/{}^{138}_{54}Xe$. The highest value of Coulomb interaction energy correspond to deformation ε_L=0.4, for ${}^{96}_{38}Sr$. and ε_H=0 for ${}^{138}_{54}Xe$.

to the Q-values Q' and Q'', deformation energies D'_{min} and D''_{min} and the total kinetic energy TKE'_{max} and TKE''_{max}, respectively. If Q' < Q'', we see from Fig. 1, that $D'_{min} > D''_{min}$. The difference between the TKE_{max} values will be higher than the difference between the corresponding Q values. It equals the sum of the differences of two a Q-values and the deformation energies.

3. INTERPRETATION OF EXPERIMENTAL DATA

3.1 COULOMB EFFECTS

In the region of cold fission, only the mass and kinetic energy distributions have been measured for reactions $^{233}U(n_{th},f)$, $^{235}U(n_{th},f)$ and $^{239}Pu(n_{th},f)$. Let us take, for example, the TKE-line corresponding to the reaction $^{235}U\ (n_{th},f)$ presented in Fig. 8. We see as first appro-

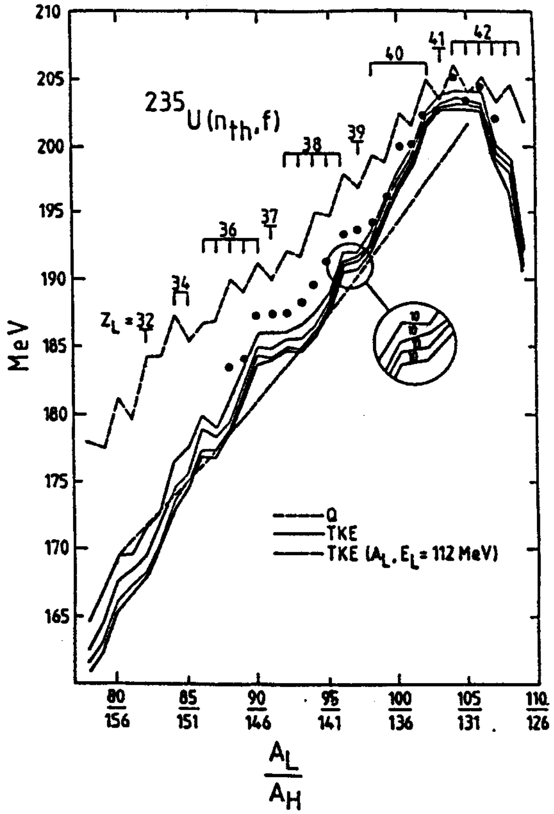

Fig. 8: Maximal Q-values (- - -); equi-probability lines for total kinetic energy, TKE (—) [16] and calculated maximal value of the Coulomb interaction energy (CE_{max}) [8] in function of the mass fragments ratio A_L/A_H in the reaction $^{235}U(n_{th},f)$.

Table 1: *Reaction $^{235}U(n_{th},f)$.. Yields Y and Y' of two light fragment charges Z_L and Z_L' corresponding to very close Q-values, (Ref. [14]), Q and Q', respectively, the light fragment kinetic energy were fixed to E_L= 108 MeV. These results were obtained by W. Lang. et. al. [4].*

A_L	TKE (MeV)	Z_L	Z_L'	Q MeV	Q' MeV	Y(%) Ref. [4]	Y'(%) Ref. [4]
103	196	40	42	200.5	200.8	22.6 ± 3.2	24.0 ± 3.3
102	194.5	41	42	198.8	204	39.0 ± 2.4	4.9 ± 1.7
101	199	39	41	199	199	4.5 ± 0.9	21.7 ± 2.3
100	191	41	42	194.5	194	8.6 ± 5.9	0.7 ± 0.7
99	189	39	40	197.8	197.6	45.0 ± 3.1	47.21 ± 3.4
98	188.5	38	40	197.8	198	33.0 ± 5.5	21.8 ± 2.9
98	188.5	37	41	188.5	189.5	0	1.8 ± 1.3
97	186.2	38	39	195.4	196	54.8 ± 33.0	39.1 ± 3.0
96	185	39	40	192.4	193	12.5 ± 1.5	1.4 ± 0.9
95	184	37	39	191.8	192.1	15.8 ± 1.5	10.5 ± 1.5
93	180.5	37	38	191	191	64.2 ± 3.7	21.8 ± 3.5
92	179.5	36	38	191	191.4	53.4 ± 3.1	6.3 ± 1.9
91	178.4	36	37	188.8	189	75.9 ± 3.3	19.7 ± 3.1
90	176.8	37	38	186.1	186.8	4.4 ± 2.6	0
89	175	35	37	185.8	186.5	29.3 ± 2.3	3.5 ± 2.1
87	172.5	35	36	185.2	185.9	45.6 ± 3.0	10.1 ± 2.0
86	171	34	36	186.1	186.1	83.8 ± 5.4	0
85	169.4	33	35	179.8	184.0	6.7 ± 1.7	3.3 ± 2.1
84	168.4	33	35	179.6	179	19.8 ± 2.1	4.4 ± 3.2

ximation, that the TKE-values and the fragment charges corresponding to the most compact scission configurations as a function of A_L, are those given by the maximal Q-value [13,16]. Moreover, oscilations in the TKE-line [14] are seen.

From A_L=87 to A_L=90, the slope of the TKE-lines as a function of A_L is TKE/A_L =2.5 MeV/amu while from A_L=90 to A_L=92 the slope is TKE/A_L =0. A similar behaviour of the TKE-lines, as shown for the reaction $^{235}U(n_{th},f)$, is also found in the reaction $^{233}U(n_{th},f)$ and $^{239}Pu(n_{th},f)$ [6,7].

The diminishing of TKE/A_L is due to the variation of Z_L, from Z_L =36 (A_L =86-90) to Z_L =37 and 38 (A_L =91, 92). Assuming that the most compact scission configurations correspond to the maximal Q-value, the oscilations cannot be explained. In Sect. 2.1 we have learnt, when two charges Z_L correspond to very close Q-values, the Coulomb effects favour the yield of the lowest Z_L. Let us take the case of $^{235}U(n_{th},f)$ in order to see the influence of the Coulomb effect on the charge corresponding to the most compact scission configuration.

In the region of A_L = 86-90, the Z_L-value corresponding to the maximal Q- value is Z_L=36, and all neighbouring Q-values are very low compared to the measured one. Then, we expect that for A_L = 86-90, the most compact scission configuration corresponds to Z_L = 36. For A_L =91,92 and 93, the highest Q-value corresponds to Z_L=37 (Q = 189 MeV), Z_L=38 (Q=191.4 MeV) and Z_L = 38 (Q = 191 MeV), respectively. For those mass chains the charges Z_L = 36 (Q = 188.8 MeV) and Z_L = 37 and 38 (Q = 191 MeV), respectively, have Q-values very close to the highest ones. Then, the Coulomb effect has a trend to shift for the most compact configuration the charges downward to Z_L = 36 (A_L = 91,92) and Z_L = 37 (A_L = 93). As in the mass region A_L = 90-92 the most compact scission configurations correspond to Z_L = 36, the highest TKE-lines are expected to be horizontal, in agreement with experimental TKE-lines which present a shoulder in A_L=90- 92. From A_L=92 to A_L=93 the charges correspon-

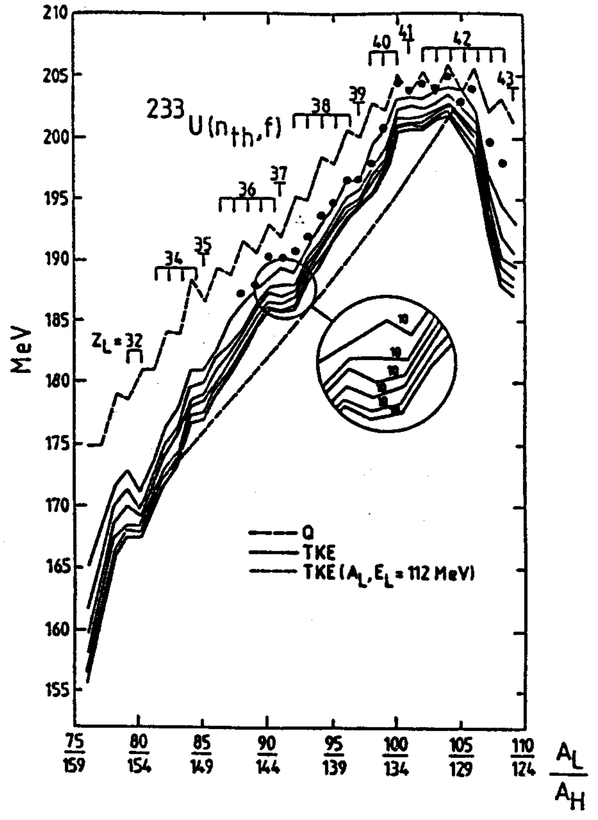

Fig. 9: Similar to Fig. 8, for the reaction $^{233}U(n_{th},f)$.

ding to C_{max} are predicted to change from Z_L=36 to Z_L=37 (or 38), respectively. As the lowest Z_L are favoured by the Coulomb effect, a relatively slow change in TKE_{max} value is predicted to be found between A_L=90 and 93 in agreement with the experimental TKE-lines.

W. Lang et al. [4] have measured the charge and mass distribution in E_L windows as high as 108.0 MeV. This window corresponds to the TKE-lines 10 MeV lower (in average) than the maximal Q-line. Nevertheless, for A_L=91 and 92, the charge Z_L=36 has a higher yield (75.9 % ± 3.3 and 53.4 % ± 3.1, respectively) in comparison to the yield of Z_L=37 (19.7% ± 3.1) and Z_L = 38 (6.3 % ± 1.9), respectively, in agreement with the predictions from the Coulomb effects (see Table 1). For A_L=93, the charge Z_L=37 has a higher yield (64.2 % ± 3.7) than for Z_L = 38 (21.8 % ± 3.5).

Another case, where the Coulomb effect can be seen, in the reaction $^{235}U(n_{th},f)$, is the mass region A_L=96-98, the charges of which for maximal Q-values are Z_L=38 (Q=197.2 MeV), Z_L=39 (Q=196 MeV) and Z_L=40 (Q=198 MeV). If one assumes that those charges correspond to the highest TKE-line, this line would show no shoulder as observed experimentally. Again, one can interprete the shoulder by the existence of the charge Z_L=38 in the chain A_L=98, the Q-value of which (=197.8 MeV) is very close to the one corresponding Z_L=40. Z_L=38 will be favoured by the Coulomb effect. The experimental results, for E_L=108 MeV (TKE=179.5 MeV, for A_L=98), obtained by W. Lang et al. [4] show that the yield of the charge Z_L = 38 (33% ± 5.5) is higher than the yield of the charge Z_L = 40 (1.8 % ± 2.9).

The experimental results, obtained by W. Lang et al. [4], presented in table 1, show that the Coulomb effect favours fragmentations corresponding to Q-values other than the highest ones. For example, for A_L=89, the maximal Q-value (187.8 MeV) is obtained for Z_L=36. The yield of charge Z_L=35 (29.3% ± 2.3), Q-value =185 MeV, is higher than the yield of Z_L =37 (Y=3.5% ± 2.1) in despite of its lower Q-value.

According to Eq. (3), the Coulomb effect diminishes with increasing Z_L. In the experimental data there is no Coulomb effect observed for Z_L = 40-42 (A_L=100-106), the region corresponding to the highest values of Z_L. Moreover, as it was shown in subsection 2.1., in this region very soft light fragments are found which are expected to decrease the Coulomb effect.

One could argue that the fragment charge was not measured at the limit TKE_{max} and it could be difficult to see the Coulomb effect. Nevertheless, J. Trochon et al. [15] identified, in the case of $^{235}U(n_{th},f)$, the surviving charge for the highest values of TKE. The charges found correspond in most cases to the maximal Q-value. But the surviving charge for the fragmentation for A_L/A_H=91/141 is Z_L/Z_H = 36/54 (Q=188.8 MeV), in variance with the maximal Q-value (189 MeV) corresponding to the charge fragmentation 37/55.

3.2 INFLUENCE OF THE Q-VALUE

In order to separate the influence of the Q-value from other effects one takes the fragmentations $^{104}_{42}Mo/^{130}_{50}Sn$ and $^{106}_{42}Mo/^{128}_{50}Sn$, the corresponding Q-values of which are 205.3 MeV and 204.6 MeV. In Fig. 8 one can see that the TKE_{max} corresponding to the mass fragmentation 104/130 is higher than the TKE_{max} value corresponding to the fragmentation 106/128. From considerations of energy balance, unique charges were attributed for those fragmentations [6,7].

Let us consider the fragmentations $^{96}_{38}Sr/^{138}_{54}Xe$ and $^{94}_{38}Sr/^{140}_{54}Xe$, the Q-values of which are 199.5 MeV and 197.5 MeV. One has chosen those fragmentations bacause the Q-values of their neighbouring charge splits are relatively low, making reasonable the hypothesis of pure charge fragmentations. One can observe (see Fig. 9) that the difference between the corresponding TKE_{max} values is higher than the difference between the corresponding Q-values, as expected and explained by analysis of the influence of the Q-value (subsection 2.4).

To approach the TKE_{max} values experimentally is very difficult. The mass- yield at the highest values of E_L was measured by Quade et al. [2,3]. The survival masses, at E_L=118.1 MeV, are A_L=80 and 84. Only these masses have Q-values higher than the TKE values calculated from the light fragment kinetic energy E_L=118.1 MeV. This result clearly shows a limiting aspect of the Q-value on the fission yields.

3.3 SHELL AND PAIRING EFFECTS

In the subsection 2.3 the calculation of the maximal value of the Coulomb interaction energy at scission configuration has been presented. From this calculations, follows the conclusion that for the fragmentations close to $^{104}_{42}Mo/^{130}_{50}Sn$ the maximal value of the total kinetic energy will be very close to the Q-values. The heavy fragments, neighbours of the doubly closed spherical shell nucleus $^{132}_{50}Sn$, and the light fragments in the region Z_L=40-42 and N_L=60-64, corresponding to deformed nuclei [16] constitute the fragmentations with the lowest excitation energy. The interplay of shell and pairing terms influences the properties of deformations in nuclei. These properties could be also responsible for the structures in the TKE-lines. The method presented in the subsection 2.3 was used to calculate the C_{max} values for the reaction $^{233}U(n_{th},f)$ which are in agreement with the highest TKE-lines, as it is shown in Fig. 8 and 9.

However, the calculated C_{max}-values present an odd-even effect in the region A_L=100-106, which for the smaller TKE-lines in this mass region is not observed. The odd-even effect in the TKE-lines could be washed out by the fact that the energy necesary to deform an even-even fragment, is higher than the energy to deform an odd-mass fragment, as was found in the results of calculations. Still, this difference of the deformation energy for the most compact configurations is smaller than the difference of the Q-values.

4. NUCLEON PAIR BREAKING AND ODD-EVEN EFFECTS

Excepting the low fission yield region close to the highest limit of E_L, studied by U. Quade et al. [2,3] for the case of ^{234}U, there is no evident odd-even effect on mass yield at light fragment kinetic energy windows. Neither the TKE-lines, presented in Figs. 8 and 9 for ^{235}U and ^{234}U, respectively, show an odd-even effects as expected from the odd-even effect on charge distributions.

The absence of odd-even effects on the mass yield, Y(A), suggests that there is at least one nucleon (proton or neutron) pair broken. If one assumes that there is no more than one nucleon pair broken, which is reasonable at very high E_L windows, one can show [7] that the odd-even effects on charge, δZ, and neutron number, δN, distributions are related by

$$\delta Z + \delta N = 1 \qquad (5)$$

The existing experimental results obtained by U. Quade [3] reach the window E_L=110.55 MeV as the highest limit. This window is very low, compared to the maximun Q-value, and the corresponding fragments have an excitation energy around 10 MeV. For that window, δZ=0.38 and δN=0.11 was obtained. These values do not hold the relation (5). The even-A fragmetations could be odd-Z-odd-N fragmentations, whose proportion in relation to the total number fragmentations is given in Ref. [7]:

$$P_{00} = 1/4\,(1+\delta A-\delta Z-\delta N) \tag{6}$$

Then, for the indicated E_L-window one obtains P_{00}=0.12. That means for E_L=110.55 MeV, at least 12% of fragmentations will have at least 2 nucleon (one proton and one neutron) pairs broken.

Let us assume the probability, p, that the broken pair nucleons end up in different fragments [6,7]. Then δZ and δN are the probabilities that no proton and neutron pair, respectively, are broken. One can also say that δA is the probability of no nucleon pair breaking in the fission process. In this approach one can say, from experimental results obtained by W. Lang et al. for ^{236}U [4] that the probability to have paired states of proton (neutrons) increase with E_L. Nevertheless, the probability of nucleon (proton or neutron) pair breaking is almost 1, even for E_L =110.55 MeV.

This conclusion follows from the experimental δA=0, obtained in this region. In other words, there is always at least one nucleon pair broken in the fission process.

Experimental mass yield were obtained by U. Quade et al. for E_L-values higher than 110.55 MeV [2,3]. δA is still zero up to E_L=115.2 MeV. For E_L-values higher than 116.1 MeV, one can observe an odd-even effect on mass yield. This suggests that, for this vanishing tail $Y=10^{-7}$, there is no nucleon pair breaking.

It appears clear that for cold fission there is nucleon pair breaking. The question, that one has to discuss, is the number of broken pairs and the proportion of proton and neutron pair broken, respectively. From the odd- even effect on the kinetic energy in function of charge, W. Lang et al. [4] had estimated that in $^{235}U(n_{th},f)$ 25% of all fission events are superfluid, i.e. in a paired state. This conclusion was obtained assuming that the non- superfluid fraction contains one broken proton pair which shifts the average kinetic energy by 0.7 MeV.

5. SCHEMATIC MODEL OF TWO HARD CORES

Fragment mass, neutron and proton number distributions are limited by lowest and highest numbers. One can see, for example, the results obtained by W. Lang et al. [4] for $^{235}U(n_{th},f)$. Let us assume that the minimum proton numbers Z_{Lm} and Z_{Hm} are obtained for light and heavy fragments, respectively, and N_{Lm} and N_{Hm} are obtained for the corresponding minimum neutron numbers. One can also define the corresponding minimum mass numbers as A_{Lm} and A_{Hm}, respectively. The existence of the mentioned minimum numbers suggests that two pre-fragments constitute two hard cores in the fission process: (Z_{Lm}, N_{Lm}; Z_{Hm}, N_{Lm}). The nucleos orbiting around the two cores are responsible for the charge and mass distribution obtained in the final fragments. The numbers of neutron of proton pairs orbiting around the two cores in the case of ^{236}U will be given by the relations

$$N_N = (\,144 - N_{Lm} - N_{Hm}\,)\,/\,2 \tag{6a}$$

and

$$N_Z = (92 - Z_{Lm} - Z_{Hm}) / 2 \tag{6b}$$

respectively. The total number of nucleon pairs orbiting the two cores will be given by

$$N_A = N_Z + N_N \tag{6c}$$

If one assumes that all the orbiting nucleon pairs have the same probability, q, to be broken, the probability for a broken pair to be a proton pair is given by the relation

$$\varepsilon = N_Z / N_A \tag{7}$$

Let us adopt the hypothesis that the probability, p, for the nucleons of a broken pair to end up in different fragments is 1/2 [6,7]. The combinatorial analysis proposed by H. Nifenecker et al. [17] give the relation [18]

$$\delta Z = (1 - q\varepsilon)^{N_A}, \tag{8a}$$

$$\delta N = [1 - q(1 - \varepsilon)]^{N_A}, \tag{8b}$$

and

$$\delta A = (1 - q)^{N_A}. \tag{8c}$$

Let us apply these relations to the experimental results for $^{235}U(n_{th},f)$ obtained by W. Lang. et al. [4]. For the window E_L=88.5 MeV, one can deduce that, approximately,

$N_{Lm} = 50$;	$N_{Hm} = 80$,
$Z_{Lm} = 34$;	$Z_{Hm} = 50$.

Then, from relation (6) one obtains

$N_A = 7$ and $N_Z = 4$,

which, using relation (7), gives

$$\varepsilon = 0.36$$

The experimental result Z = 0.18 will be reproduced by formula (8a), using q = 0.4. Then, from formula (8b) one gets $\delta N_{cal} = 0.038$, which agrees with the experimental result $\delta N_{exp} = 0.024 \pm 0.016$.

If one takes into account the totality of fission events, the assumptions one has adopted predict odd-even effects on the average total kinetic energy as a function of charge, neutron and mass number, given by the relations [18]

$$\delta Z_{TKE} = \Delta E \frac{2\delta Z}{1-\delta Z^2} N_A \left(\frac{q\varepsilon}{1-q\varepsilon} \right) q, \qquad (9a)$$

$$\delta N_{TKE} = \Delta E \frac{2\delta N}{1-\delta N^2} N_A \left(\frac{q\varepsilon}{1-q\varepsilon} \right) q, \qquad (9b)$$

$$\delta A_{TKE} = \Delta E \frac{2\delta A}{1-\delta A^2} N_A q, \qquad (9c)$$

respectively, where ΔE is a parameter adopted as the value of energy necessary to break a nucleon pair.

From the same experimental data one takes the window $E_L = 108$ MeV. The charge and neutron number distribution suggest that

$$N_{Lm} = 52, \qquad N_{Hm} = 82$$

and

$$Z_{Lm} = 36, \qquad Z_{Hm} = 50.$$

In a similar way as one has proceeded for the window E_L=88.5 MeV: one gets N_A=5, N_Z=3, =0.38. From δZ_{exp}=0.32 one obtains q=0.35 and N_{cal}=0.14 which has to be compared with δN_{exp}=0.08 0.02.

The odd-even effect in the energy integrated yield is $\delta Z_{exp}=0.237\pm0.007$ and δN_{exp}= 0.054 ± 0.008. If one sees the mass distribution in Ref. [4] one can say that A_{Lm}=82 and A_{Hm} =106. Then N_A=12. From relations (8a) and (8b) one obtains ε =0.34 and q=0.33. Then from relation (9a) follows

$$\delta Z_{TKEcal} = 0.25\ \Delta E.$$

If one assumes that ΔE = 2.5 MeV, the calculated δZ_{TKEcal} will be 0.63 MeV, Which would be compared δZ_{TKEexp} =0.7 MeV, obteined by W. Lange et al. [4,19]. G. Mariolopoulos et al. [19] have obtained δZ_{TKE} = 1.1 MeV.

6. CONCLUSION

One has studied the experimental results on charge, mass, and kinetic energy distribution for fragments from the thermal neutron induced cold fission of ^{233}U, ^{235}U. From these results, one can conclude that the Coulomb interaction energy as a function of fragment deformation, as well as the fragment energy as a function of deformation, influence the scission configuration with a similar importance as the role played by the Q-value. The oscillations in TKE_{max} as a function of the light fragment mass, can be interpreted by the Coulomb effect. The Coulomb effect is higher for the most asymmetric fragmentations and it is negligeable for the soft fragments at A_L=100.

Proton, neutron, and mass number distributions for fragments suggest the existence of two hard cores in the pre-scission configurations. The orbiting nucleons are disponsible of the indicated distributions. Odd-even effects on proton and neutron numbers as well as the odd-even effect on average kinetic energy, suggest that in the total orbiting nucleons pairs 23% of proton pairs and 5.4% of neutron pairs are not broken in the reaction ^{235}U(n_{th},f). The lowest excitation energy is obtained for fragmentation neighbours to $^{104}_{42}$Mo, $^{130}_{50}$Sn in the reaction ^{233}U(n_{th},f), because the light fragment is deformed in the ground state and its deformation is by chance the same as is needed to have a Coulomb interaction energy close to the Q-value.

Finally, from results obtained by Quade et al [3] related to mass distribution, one has to say that there exists a very part ($Y=10^{-7}$) of the fission events that do not have pair breaking. The rest of events have at least one nucleon (proton or neutron) pair broken.

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