FISSION : NUCLEON PAIR BREAKING BEFORE SCISSION

Modesto MONTOYA

Instituto Peruano de Energía Nuclear, Apt. 1687, Lima Perú

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ABSTRACT

In order to explain the odd-even effect observed in low energy fission fragment distributions it has been recently required a double mechanism of nucleon pair breaking: before scission (early pair breaking) and at scission (late pair breaking), respectively. In the present work we show that, using the same formulae but considering only the early pair breaking mechanism, one can reproduce fairly well all the available experimental data on the odd-even effects.

RESUMEN

Para explicar el efecto par-impar observado en las distribuciones de fragmentos de fisión a baja energía, se ha requerido recientemente un doble mecanismo de ruptura de parejas de nucleones : antes de la escisión (ruptura temprana de parejas) y en la escisión (ruptura tardía de parejas), respectivamente. En el presente trabajo se muestra que, usando el mismo formalismo pero considerando sólo el mecanismo de ruptura temprana, se puede reproducir bien los datos experimentales disponibles sobre los efectos par-impar.

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1.- INTRODUCCION

The mostly measured fission fragment parameters are the mass (A), proton (Z), neutron (N) numbers and the kinetic energy (E) of the fragments from the thermal neutron induced fission of ^{235}U. For this and other fissioning systems structures with a period of 5 a.m.u. were found on the mass distribution. They were first related to the maximun value of available energy as a function of mass and charge ratios. This suggested that a preference for splits into even charge exists [1]. The measured charge distribution confirmed the so called odd-even effect on charge distribution [2, 3]. On the other hand the average values of kinetic energy of the fragments present also and odd-even effect i.e. the average kinetic energy of even charge fragments is larger than of the neighboring odd charge fragments [3, 4]. In order to explain these odd-even effects H.-G. CLERC et al. [3] supposed that in a fraction of the fissioning events a proton-pair is broken in each event while in the other fraction no nucleon pair breaking occurs. This fraction was called the superfluid fraction. It was also assumed that a nucleon pair breaking diminishes by a certain amount ΔE of the total kinetic energy of fragments.

H. NIFENECKER et al., analyzing the above indicated odd-even effect as well as those on spontaneous fission of ^{252}Cf, suggested [5] that the proton pair breaking is produced at scission. Their hypothesis was that a proton pair breaking is produced only in the odd charge fragmentations.

H.-G. CLERC et al. measured the proton and neutron number distributions as a function of light fragment kinetic energy. These distributions indicate that odd-even effects increase with the fragment kinetic energy. C. SIGNARBIEUX et al. showed experimentally that the fragment mass distribution, contrary to the Z and N distributions exhibits no evidence for odd-even effect for any value of fragment kinetic energy. [6, 7]. This result was explained by the authors assuming that for each fission event there is at least one broken nucleon pair, and that nucleon pair breaking occurs before scission. The null odd-even effect on mass and the high odd-even effects on proton and neutron number distributions are explained [7, 8] by an anti-correlation between the numbers of proton and neutron pairs broken in the process.

H. NIFENECKER et al. proposed, in a recent publication [9], a model considering two pair breaking mechanisms : the early pair breaking mechanism i.e. pair breaking before scission and the late pair breaking mechanism i.e. pair breaking at scission. For early pair breaking mechanism the separated nucleons end with an equal probability in the same fragment as well as in different fragments. While for the late pair breaking H. NIFENECKER et al. assumed that the separated nucleons end in different fragments. They also assumed that the two mechanisms are independent. Using this two pair breaking mechanisms the authors reproduced the odd-even effects for several systems.

The purpose of the present work is to show that the early pair breaking mechanism as defined by H. NIFENECKER et al. is sufficient to reproduce the available experimental results on odd-even effects.

2.- *FORMALISM FOR TWO NUCLEON PAIR BREAKING MECHANISMS*

Let ${}^{Z}Y_e$ and ${}^{Z}Y_o$ be the yields of fragments with even and odd numbers of protons, respectively. Consider the normalization ${}^{Z}Y_e + {}^{Z}Y_o = 1$. The odd-even effects on fragment proton number distribution is defined by

$$\delta Z = {}^{Z}Y_e - {}^{Z}Y_o \qquad (1a)$$

The average kinetic energy of fragments with even and odd Z are defined by ${}^{Z}E_e$ and ${}^{Z}E_o$, respectively. The oddeven effect on the average fragment kinetic energy relative to the proton number (charge) is defined by

$$\delta\, {}^{Z}\bar{E} = {}^{Z}\bar{E}_e - {}^{Z}\bar{E}_o \qquad (1b)$$

The above odd-even effects defined for the fragment proton number (Z) can be generaliz ed for the neutron number (N) and the mass number (A) respectively. Let T be a parameter that can be Z, N or A.

We define the odd-even effects on T by

$$\delta T = {}^{T}Y_e - {}^{T}Y_o , \qquad (2a)$$

$$\delta\, {}^{T}\bar{E} = {}^{T}\bar{E}_e - {}^{T}\bar{E}_o \qquad (2b)$$

In order to relate the odd-even effects to pair breaking mechanisms one defines the values Q_{ij}^{kl} as the probability for i proton, j neutron pairs to be broken before scission and k proton, l neutron pairs to be broken at scission. It is assumed that the separated nucleons from breaking before scission and with the same probability in the same fragment as well as in different fragments [3,4,9]. From the above indicated definitions and assumptions one can obtain the following formulae :

$$\delta Z = \sum_{j,k,l} (-1)^{k} \Omega^{kl}_{0j} \qquad (3a)$$

$$\delta N = \sum_{i,k,l} (-1)^{l} \Omega^{kl}_{i0} \qquad (3b)$$

$$\delta A = \sum_{k,l} (-1)^{k+l} \Omega^{kl}_{00} \qquad (3c)$$

Suppose that a nucleon pair breaking diminishes, by a amount ΔE, the fragment kinetic energy. Then, considering the definitions and assumptions indicated before, it follows that

$$\delta Z_E = \frac{2\Delta E}{1-\delta Z^2}\left\{\delta Z.\bar{n} - \sum_{j,k,l} (j+k+l)(-1)^{k}\Omega^{kl}_{0j}\right\} \qquad (4a)$$

$$\delta N_E = \frac{2\Delta E}{1-\delta N^2}\left\{\delta N.\bar{n} - \sum_{i,k,l} (i+k+l)(-1)^{l}\Omega^{kl}_{i0}\right\} \qquad (4b)$$

$$\delta A_E = \frac{2\Delta E}{1-\delta A^2}\left\{\delta A.\bar{n} - \sum_{k,l} (k+l)(-1)^{k+l}\Omega^{kl}_{00}\right\} \qquad (4c)$$

Where n is the number of broken nucleon pairs and $\bar{n}$ is the average value of n :

$$n = i + j + k + l \qquad (5a)$$

$$\bar{n} = \sum_{i,j,k,l} (i+j+k+l)\ \Omega^{kl}_{ij} \qquad (5b)$$

Where the indices i, j, k, l go from 0 to ∞, i.e.

$$i, j, k, l \in [\,0\,,\ \infty\,]$$

3. - NUCLEON PAIR BREAKING BEFORE SCISSION

Consider only the early pair breaking mechanism. By definition there is no pair breaking at scission. In other words

$$Q_{ij}^{kl} = 0 \quad \text{for} \quad k > 0 \quad \text{or} \quad l > 0$$

Let us define

$$Q_{ij} = Q_{ij}^{00}$$

Substituting this definition into formula (3) and (4) we obtain

$$\delta Z = \sum_j Q_{0j} \tag{6a}$$

$$\delta N = \sum_i Q_{i0} \tag{6b}$$

$$\delta A = Q_{00} \tag{6c}$$

$$\delta Z_{\bar{E}} = \frac{2\,\Delta E}{1 - \delta Z^2} \left\{ \delta Z.\bar{n} - \sum_j (j)\, Q_{0j} \right\} \tag{7a}$$

$$\delta N_{\bar{E}} = \frac{2\,\Delta E}{1 - \delta N^2} \left\{ \delta N.\bar{n} - \sum_i (i)\, Q_{i0} \right\} \tag{7b}$$

$$\delta A_{\bar{E}} = \frac{2\,\Delta E}{1 - \delta A^2} \, \delta A.\bar{n} \tag{7c}$$

As an example it has been shown in ref. [8] that the following matrix :

$$Q = \frac{1}{10} \begin{vmatrix} 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 \end{vmatrix}$$

fits rather well the experimental data

$$\delta Z_{\bar{E}} = 1.3\,\Delta E$$

$$\delta Z = 0.3$$

$$\delta N = 0.1$$

$$\delta A = 0.$$

H. NIFENECKER et al. proposed a binomial type formula for Q_{ij} :

$$Q_{ij} = C_i^n \epsilon^i (1-\epsilon)^{i} P_N(n) \quad (8a)$$

Where

$$P_N(n) = C_n q^n (1 - q)^{N-n} \quad (8b)$$

N is the maximun number of broken nucleon pairs, q is the probability for a pair to be broken, ϵ is the probability for a broken pair to be proton one. Inserting (8) in formulae (6) and (7), gives

$$\delta Z = (1 - q\epsilon)^N \quad (9a)$$

$$\delta N = 1 - q(1 - \epsilon)^N \quad (9b)$$

$$\delta A = (1 - q)^N \quad (9c)$$

$$\delta Z_E = \Delta E \frac{2\delta Z}{1 - \delta Z^2} N \frac{(1 - \delta Z^{1/N})}{\delta Z^{1/N}} (\delta Z^{1/N} + \delta N^{1/N} - 1) \quad (10a)$$

$$\delta N_E = \Delta E \frac{2\delta Z}{1 - \delta N^2} N \frac{(1 - \delta N^{1/N})}{\delta N^{1/N}} (\delta Z^{1/N} + \delta N^{1/N} - 1) \quad (10b)$$

$$\delta A_E = \Delta E \frac{2\delta A}{1 - \delta A^2} (1 - \delta A^{1/N})$$

The value of ΔE is estimated, from the odd-even effects on masses, to be equal to 2.5 MeV.

4- AVERAGE ODD-EVEN EFFECTS

The odd-even effects δZ and $\delta^Z E$ for the total fission events were measured for the following systems: the thermal neutron induced fission of ^{235}U, indicated by ^{235}U (th.n.,f.); the 3MeV neutron induced fission of ^{235}U, indicated by ^{235}U(3MeV n.,f.); the spontaneous fission of ^{252}Cf, indicated by ^{252}Cf (s.f.); and the slow neutron induced fission of ^{229}Th, indicated by ^{229}Th (s.n.,f.). For the case of ^{235}U (th.n.,f.) the two existing data can be reproduced by formula (9) and (10) with the values of N, q, ϵ, $\bar{n}$, $\sigma^2 n$ presented in the following table :

	δZ	δN	$\delta^Z E$	N	q	ϵ	n	$\sigma^2 n$
Ref. [3]	0.237	0.054	ap. 0.7	5.5 ± 0.5	0.66 ± 0.02	0.36 ± 0.01	3.63	1.23
Ref. [4]	0.22	0.06	0.8 ± 1.5	5.5 ± 1.5	0.64 ± 0.1	0.37 ± 0.01	3.52	1.27

H. NIFENECKER et al. have analyzed the case of ^{235}U (3MeV n., f) in order to estimate the value of ϵ for pair breaking at the saddle. They supposed that pair breaking at saddle and pair breaking during the descent until scission are independent. They estimate there are $\Delta N = 2.5$ more broken nucleon pairs than for ^{235}U(th.n.,f.). Then the odd-even effect on proton number distribution is given by

$$\delta^{3MeV} Z = (1 - \epsilon)^{\Delta N} \delta^{th} Z \qquad (11)$$

Using the experimental results $\delta^{3MeV} Z = 0.06$ and $\delta^{th} Z = 0.22$ H. NIFENECKER et al obtained $\epsilon = 0.4$. They notice that for the fissioning system Z/A = 0.39. We have seen that for average odd-even effects $\epsilon = 0.37$. This suggests that the probability for a broken pair to be a proton one is proportional to the number of proton pairs existing in the fissioning system. Comparing $\epsilon = 0.37$ and the estimated value for pairs breaking at saddle one can say that nucleon pair breaking in ^{235}U (th.n.,f.) is mostly produced close to the saddle.

The average odd-even effects for ^{252}Cf(s.f.) and ^{229}Th(s.n.,f.) were also reproduced by formulae (9) and (10). The main origin of the incertainty is on $\delta^Z E$. Neutron emission does not permit a high resolution of fragment kinetic energy. We present the results on the following table :

	δZ	$\delta^Z\bar{E}$	N	q	$\bar{n}$	$\sigma^2 n$
^{252}Cf (s.f.) [4]	0.12	0.8 ± 0.4	12 ± 5	0.44 ± 0.3	5.28 ± 0.04	3.0 ± 1.5
^{229}Th (s.n.,f) [4]	0.35	1.3 ± 0.3	6 ± 1.5	0.43 ± 0.2	2.6 ± 0.2	1.5 ± 0.4

The incertainty on $\delta^Z\bar{E}$ produces an uncertainty on q and N values. However the uncertainty of $\bar{n}$ is negligible.

5.- ODD EVEN EFFECTS AS A FUNCTION OF FRAGMENT KINETIC ENERGY

H.- G. CLERC et al. have measured [3] δZ and δN for several fixed values of light fragment kinetic energy (E_L) from 88.5 to 108 MeV for the case of ^{235}U (th. n., f.). In order to calculate the N, q and ϵ values from equations (9) and (10) one needs three values of odd-even effects. We can however assume that value of ϵ is the same as for average odd-even effects. If so we obtain the results presented in the following table :

E_L (MeV)	δZ	δN	N	q	$\bar{n}$	$\sigma^2 n$
108	0.33	0.086	2.45	1.00	2.45	0.10
103	0.27	0.075	3.9	0.77	3.	0.69
98.3	0.23	0.045	3.44	0.95	3.23	0.16
93.4	0.20	0.034	3.80	0.93	3.55	0.23
88.5	0.18	0.024	3.75	0.99	3.74	0.01

Here we used ϵ = 0.37 as calculated from average odd-even effects measured by G. MARIOLOPOULOS et al. [4]. The values of q, N and $\sigma^2 n$ depend strongly on ϵ. While $\bar{n}$ is approximately independent of ϵ. Let us use ϵ = 0.36 deduced from data obtained by H.- G. CLERC et al. [3]. Then values of N, q and ϵ corresponding to the same data presented above are the following :

E_L (MeV)	N	q	$\bar{n}$	$\sigma^2 n$
108	2.6	0.96	2.49	0.36
103.1	5.0	0.63	3.17	1.16
98.3	4.2	0.82	3.43	0.63
93.4	5.0	0.77	3.86	0.89
88.5	4.5	0.88	3.96	0.47

One can observe that the value of the maximun number of broken nucleon pairs dos not increase by diminishing E_L. This seems abnormal, however the average number of broken nucleon pairs obeys the reasonable decreasing function of E_L. One must notice that if for the total fission events the probability of pair breaking obeys binomial type formula for fixed values of kinetic energy this is not necesarily the case. Thus we must be careful when applying formula (9) for fixed values of fragment kinetic energy.

6.- *ULTRA COLD FISSION*

P. ARMBRUSTER et al have measured [10] δZ and δN for $E_L = 112$ MeV from ^{233}U (th.n.,f.). They considered their result ($\delta Z = 0.46$ and $\delta N = 0.11$) and the extrapolation of the H.- G. CLERC et al. results ($\delta Z = 0.40$ and $\delta N = 0.11$) esti - mating δZ to be equal to the average $\delta Z = 0.43$. Using this value and $\delta N = 0.11$ in formula (9) one obtains $N = 1.1$, $q = 1$ and $\epsilon = 0.33$. The linear extrapolation of H.- G. CLERC et al. results gave in fact $\delta Z = 0.35$ and $\delta N = 0.11$. With these values one obtains $N = 3$, $q = 0.93$, $\bar{n} = 2.32$ and $\sigma^2 n = 0.16$ for $\epsilon = 0.37$.

The δZ and δN presented above are measured after neutron emission. This is the cause of errors on δN , δA and fragment kinetic energy. The increasing values of δZ , δN as a function of E_L suggested that at very high values of fragment kinetic energies, mostly even-even fragments would be obtained. Surprising experimental results [6,7] show in contrary to the suggestion for high values of kinetic energy that there are - odd mass fragments with the same probability as the even mass fragments. In other words $\delta A = .0$. On the other hand for the very high value of E_L each mass ratio seems to select a single charge ratio. Consider that this charge ratio corresponds to the maximum value of available energy which is a function of Z. Then from mass tables we can see that for each 10 values of masses there are 8 even and 2 odd charge fragmentations. This means

$$\delta Z = 0.6$$

For the same fragmentations there are 7 even and 3 odd neutron number fragmentations i.e.

$$\delta N = 0.4$$

These values are compatible with $N = 1$, $q = 1$ and $\epsilon = 0.4$.

In the regions of very high kinetic energy we must be careful in analyzing the odd-even effects. Sometimes the available energy does not permit proton or neutron pair breaking. This is the case for mass regions where the available energy forbids odd charge fragmentation. Then $\delta Z = 1$ and $\delta N = 0$ (because $\delta A = 0$). The corresponding parameters to these values are $q = 1$, $N = 1$ and $\epsilon = 0$. For the case of ^{235}U (th.n.,f.) the above example occurs for the total fragments kinetic energy higher than 203 MeV. There exists also a region for which $\delta Z = 0$ and $\delta N = 1$. These values are reproduced by $q = 1$, $N = 1$ and $\epsilon = 1$.

7.- CONCLUSION

The experimental results on odd-even effects are well reproduced by a model in which the nucleon pairs are broken early during the descent of the fissioning system from saddle to scission. The probability for a broken nucleon pair to be a proton one is very close to the fraction of protons pair existing in the fissioning systems ($Z/A = 0.39$). This result reinforces the above conclusion. H. NIFENECKER et al. had proposed [9] a model of two pair breaking mechanisms in order to show that the hypothesis of a late pair breaking mechanism is compatible with experimental result. However they have estimated the values of certain parameters (probability for a pair broken at saddle to be a proton one; the similar parameter corresponding to the scission; and the probability for a pair to be broken at scission) from data in critical energy regions.

The average number of broken nucleon pairs estimated from experimental results on odd-even effects are 2.6 for ^{229}Th(s.n.,f.) ; 3.5 for ^{235}U(th.n.,f.); 6 for ^{235}U(3MeV n.,f.); and 5.3 for ^{252}Cf (s.f.).

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