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Pair breaking mechanism in cold fission

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Résumé. — On montre que l'observation d'un faible effet pair-impair sur les rendements de masse des fragments de fission à haute énergie cinétique implique que les paires de neutrons soient brisées à la dernière étape du processus de fission et contredit l'hypothèse d'une forte viscosité de ce processus.

Abstract. — It is shown that the smallness of even-odd effects on the fission fragments mass yields at high kinetic energies implies a late pair breaking mechanism and contradicts the assumption of strong viscosity of the fission process.

It is a well known fact [1] that thermal neutron induced fission of ^{235}U produces more fragments with even charge than odd charge. If one defines an even-odd enhancement factor as

$$\delta = \frac{\sum Y_e - \sum Y_o}{\sum Y_e + \sum Y_o} \quad (1)$$

where Y_e and Y_o are the yields of even and odd charge fragments respectively, δ amount to 0.22 on the average. At high kinetic energies δ increases and reaches values around 0.4.

On the other C. Signarbieux *et al.* [2] using an original and powerful time difference technique have studied the fragments' mass distributions at high kinetic energies. They have found no evidence for enhanced production of fragments with even mass. This may be interpreted as a small or vanishing value of the even-odd effect on neutron numbers since strong effects exist on the proton ones. C. Signarbieux *et al.* interpret their findings as evidence for an early pair breaking during the fission process indicating a strong viscosity of the motion towards fission. In the following we show that both the proton and neutron results can be explained by the same simple pair breaking mechanism. We also show that the result obtained by Signarbieux *et al.* does not agree with early pair breaking, in contradiction with the conclusion of these authors.

In the following we suppose that the kinetic energy of the fragments is so high that, just before scission, the maximum number of broken pairs in the dinuclear

system is one. If we define a total excitation energy of the fragments as

$$E^*(Z, N) = Q_{\max}(A) - E_K$$

our condition means that we concentrate on a region of kinetic energies between Q and $Q - 2.5$ MeV for odd- A splits and Q and $Q - 5$ MeV for even- A splits. The results of Signarbieux *et al.* [2] show precisely that even- A splits with kinetic energies between $Q_{\max} - 2.5$ MeV and $Q_{\max} - 5$ MeV are produced in amounts similar to those of odd- A splits with kinetic energies between $Q_{\max}$ and $Q_{\max} - 2.5$ MeV. We recall that 2.4 MeV [3] is approximately the energy necessary to break one pair in the fragments.

Assuming there may be either zero or one pair broken during fission we define q as the probability for one pair breaking.

The probability for this pair to be a proton pair is ε_p while it will be a neutron pair with probability

$$\varepsilon_N = 1 - \varepsilon_p. \quad (1)$$

We finally define the probability p that, if a pair is broken, the two nucleons end in different fragments, giving thus rise to either two odd Z or two odd N fragments. Here we suppose that p is the same for neutrons and protons.

The probability to observe an odd- Z split is therefore :

$$Y_o^Z = pq\varepsilon_p$$

and

$$Y_e^Z = 1 - pq\varepsilon_p.$$

Similarly for neutrons

$$\begin{aligned} Y_o^N &= pq\varepsilon_N \\ Y_e^N &= 1 - pq\varepsilon_N \end{aligned}$$

We may therefore obtain the even-odd enhancement factors

$$\begin{aligned} \delta_Z &= 1 - 2pq\varepsilon_p \\ \delta_N &= 1 - 2pq\varepsilon_N \end{aligned} \quad (2)$$

and taking (1) into account we obtain :

$$\begin{aligned} \varepsilon_N &= \frac{1 - \delta_N}{2 - \delta_Z - \delta_N} \\ \varepsilon_p &= \frac{1 - \delta_Z}{2 - \delta_Z - \delta_N} \\ pq &= 1 - \frac{(\delta_Z + \delta_N)}{2} \end{aligned}$$

From the experiment, we have :

$$\delta_Z = 0.4 \quad \text{and} \quad \delta_N = 0$$

and one obtains ⁽¹⁾ :

$$\frac{\varepsilon_p}{\varepsilon_N} = 0.6.$$

The ratio of protons to neutrons in ²³⁶U is equal to 0.64 surprisingly close to the above value. This simple model therefore explains the small or vanishing even-odd effect observed on neutron number by the higher probability for a broken pair to be a neutron pair.

In the following we thus keep the values :

$$\varepsilon_p = 0.39 = \frac{Z}{A} \quad \varepsilon_N = 0.61 = \frac{N}{A}.$$

It is clear that whatever the value of p the production of odd- N fragments will be maximized for $q = 1$ since when there is no pair breaking only even- Z , even- N , fragments can be produced.

We note that the value $q = 1$ corresponds to the assumption made by C. Signarbieux *et al.* [2]. In this case one obtains :

$$\delta_N = 1 - 1.22p.$$

If a pair is broken early in the process the two nucleons might end with equal probability in the same or different fragments, thus $p = 1/2$. Here again we find the assumption made by C. Signarbieux *et al.* [2]. In this case

$$\delta_N = 0.39 = \varepsilon_p.$$

We come to the apparently paradoxical conclusion that, at very high kinetic energies, a high viscosity implies the existence of even-odd effects both proton and neutron numbers. However the reason for this behaviour is easy to understand. Whenever there is a broken proton pair, there is no neutron broken pair and therefore one obtains only fragments with even-neutron number. On the other hand if a neutron pair is broken one obtains with equal probability fragments with even- or odd-neutron numbers. Therefore the number of fragments with even-neutron number should always be larger than that of fragments with odd-neutron numbers.

It therefore appears that the smallness of even-odd effects on the neutron numbers at very high kinetic energies is contradictory to the assumption of early pair breaking. The extreme assumption $p = 1$ corresponds to that of very late pair breaking where the scission process itself is responsible for the separation of the numbers of the pair. In some cases this assumption may lead to a larger production of odd- N fragments than of even- N fragments. To obtain equal number of odd- N and even- N fragments a finite probability of no pair breaking is required. Under the assumption $p = 1$ one obtains, using the experimental values for δ_N

$$q = 0.82 \quad (q = 0.73 \text{ if one uses the data of reference [4]}).$$

From equation (2) and the experimental values of δ_N and δ_Z , it is clear that a continuous set of solutions for p and q is possible with the only constraints $0.82 < p < 1$ and $0.82 < q < 1$. However the qualitative finding of late pair breaking remains true for all these solutions.

The hypothesis of late pair breaking also explains easily the existence of even-odd effects on the average total kinetic energies when considered as a function of Z [1] as well as the striking dependence of the average charge yields even-odd effects upon the charge itself observed in the fission of ²²⁹Th [1].

In conclusion we have shown that the smallness of neutron even-odd effects at kinetic energies so high that only one pair might be broken implies a late pair breaking process, at least for those events. The difference between the proton and neutron behaviour may be simply explained in terms of the larger probability for neutron pairs to be broken due to the neutron excess. Finally in the frame of a simple late pair breaking assumption we find a rather high probability of pair breaking of about 80 %.

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⁽¹⁾ Recent values obtained with the Lohengrin mass spectrometer [4] give : $\delta = 0.46$ and $\delta_N = 0.11$ and, therefore $\varepsilon_p/\varepsilon_N = 0.61$.

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