DELAYED NUCLEAR FISSION

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Abstract

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In regions of nuclei remote from the band of β-stability, the β-decay energy Q_β reaches a large value. In heavy nuclei it may exceed the fission barrier of the daughter nucleus. In such nuclei, β-decay to excited states lying above the barrier B_f will be accompanied by fission. Fission may also occur after α-decay; however, because of the sharp dependence of the probability of α-decay on the energy of the level, states lying above the barrier B_f should be populated with vanishingly small probability. We shall therefore restrict ourselves to considering delayed fission accompanying β-decay.

Schematically, this process may be written as follows:

$$(Z,N) \xrightarrow{\beta} (Z \pm 1, N \mp 1)^* \xrightarrow{\Phi} \sum_i (Z_i, N_i),$$

where (Z,N) symbolizes the parent nucleus of the chain with proton number Z and neutron number N; (Z_i, N_i) are the nuclei produced as a result of fission; the asterisk denotes the excited state of the intermediate nucleus $(Z \pm 1, N \mp 1)$.

To determine the regions of nuclei in which delayed fission can take place effectively, one may impose the requirement that the following inequalities be satisfied for the half-lives of the parent nucleus with respect to β- and α-decays and to spontaneous fission (SF):

$$T_{1/2}(\beta) \ll T_{1/2}(\alpha), \quad T_{1/2}(SF), \tag{1}$$

as well as the inequality

$$Q_\beta(Z, N \to Z \pm 1, N \mp 1) \gtrsim B_f(Z \pm 1, N \mp 1). \tag{2}$$

Condition (1) selects the cases in which the principal type of decay of the initial nucleus of the chain is β-decay.

When condition (2) is fulfilled, the intrinsic fission time from the excited state of the intermediate nucleus does not exceed $\sim 10^{-14}$ sec. ([1]). This value of the

Figure 1: Regions of delayed fission of nuclei.

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time ensures competition of fission from the excited state with γ emission. If the binding energy of a neutron (proton) is less than Q_β, the competing process will be particle emission.

The half-lives of the initial nucleus with respect to β-transformation were determined from the data of systematics of $\log ft$ values in the region of heavy nuclei ([1],[2]), using the nomograms of work ([3]) and theoretical values of the ratio of the probabilities of electron capture to positron emission.

The half-lives with respect to α-radioactivity were calculated from the semiempirical formulas given in work ([2]).

The periods of spontaneous fission of the initial nuclei of the chain were estimated from a barrier formula ([1]), using barrier values taken from works ([1],[4]). As is known, even a small change in the value of the barrier, for example by 0.5 MeV, leads to a change in the value of the spontaneous fission period⋯

of fission by 3–4 orders of magnitude. Therefore the prediction of new regions of spontaneously fissioning nuclei located far from the band of β-stability*, as well as the prediction in the regions of superheavy nuclei (with $Z > 114$) ([1,5,6]), is difficult. However, in determining the regions of delayed fission it is only necessary to satisfy condition (1), which is fulfilled for barrier values exceeding $\sim$ 2.5 MeV. Therefore, in most cases exact knowledge of $T_{1/2}(SF)$ is not required.

Figure 1 presents the results of estimates of the boundaries of the regions of delayed fission obtained from the condition of fulfillment of inequalities (1) and

Fig. 1. Regions of delayed fission of nuclei. 1 —region of produced nuclei; 2 —neutron-rich region of delayed fission, calculated from the mass values of work ([4]); 3 —boundary of the neutron-rich region of delayed fission, calculated from the mass values of work ([2]). *a* —proton-rich nuclei—sources of delayed fission according to the mass values of work ([2]); *b* —proton-rich nuclei—sources of delayed fission according to the mass values of work ([4]).

(2), using rough mass values taken from works ([2,4]). Here, also, on the basis of the data of work ([4]), the boundaries of the nucleon-stability region have been drawn and the region of isotopes obtained at the present time has been marked by double hatching ([7,8]). It is seen that delayed fission can occur in an extensive region of neutron-rich nuclei. Its lower and left boundaries are determined by inequality (2), and the upper boundary by inequality (1). The upper boundary of the region calculated from the mass values of work ([4]) is indicated by a dashed line, since it is determined inaccurately because of the small values of the fission barriers ($B_f \lesssim 2.5$ MeV). These nuclei should, at least in part, be synthesized in supernova flashes in the process of rapid neutron capture (the *r*-process) and, to a lesser extent, in thermonuclear explosions.

In the proton-rich region the number of nuclei in which delayed fission can be observed will be small. This is explained by the fact that inequality (1), owing to the large probabilities of α-decay, is fulfilled only for nuclei not very far removed from the band of β-stability. In this case the delay time of fission, determined by the period of the preceding β-decay, reaches $10^2 \div 10^3$ sec in these nuclei. (In the neutron-rich region the delay times lie approximately in the interval $10^2 \div 10^{-1}$ sec.)

In the works of G. N. Flerov and co-workers ([9]), fission events were discovered that are associated with the isotopes ^{232}Am and ^{234}Am, with $T_{1/2}$ values equal to 1.5 and 2.6 min, respectively. In discussing the data obtained, the authors do not exclude the possibility of delayed fission of Pu isotopes after electron capture in Am nuclei. As is seen from the results of our estimates (see Fig. 1), conditions (1) and (2) are fulfilled in these nuclei, and they can be sources of delayed fission.

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* Most of the nuclei presently known to undergo spontaneous fission belong to this band.

The regions of delayed fission shown in Fig. 1 will expand if nuclei in which delayed subbarrier fission of isomers can be observed are included in them.

Delayed fission may also occur in the regions of superheavy nuclei with $Z \approx 114$ and $Z \approx 126$ (at least according to the mass estimates of Ref. [4]). The possibility is not excluded that these nuclei are formed as a result of successive β-decays of strongly neutron-rich nuclei arising in the r-process.

The phenomenon of delayed fission will be of great interest for studying the fission process in nuclei far from the band of β-stability. This phenomenon is important not only for nuclear physics but also for astrophysics. In particular, delayed fission may influence the evolution of supernovae and the shape of their light curve, and may also affect the abundances of elements (including the superheavy ones) in the Universe.

At present the authors are carrying out calculations of the intensities of delayed-fission branches.

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Note: Figure translations are in progress. See original paper for figures.