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Beta-delayed fission of extremely proton-rich nuclei in the region of mercury to polonium

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Abstract. A comprehensive series of highly sensitive experiments performed at the Dubna U400 cyclotron has resulted in the discovery of a novel region of EC(β^+)-delayed fission (ECDF). The ECDF process was established to occur in the decay chains $^{180}Tl \xrightarrow[0.97\ s]{EC(\beta^+)} {}^{180}Hg$, $^{188}Bi \xrightarrow[0.3\ s]{EC(\beta^+)} {}^{188}Pb$, and, presumably, $^{196}At \xrightarrow[0.23\ s]{EC(\beta^+)} {}^{196}Po$.

Beta-delayed fission, i.e., fission from excited states fed via EC(β^+) decay, was first discovered in 1966 at Dubna for neutron-deficient transuranium nuclei (see [1] for a review). Subsequently it was realized [1,2] that ECDF should also occur for nuclei of *considerably lighter* elements, e.g., for extremely proton-rich nuclei of Hg or Pb. Our exploratory experiments performed in 1986 fully corroborated these expectations: a striking delayed fission activity was observed in the $^{144}Sm+^{40}Ca$ reaction and explained as being due to the ECDF of ^{180}Hg. A short account of these first results was published in [3]. Reported below are improved data on ECDF around ^{180}Hg as well as new results revealing other examples of ECDF in the preactinide region.

For producing very proton-rich nuclei in the region of Hg - Pb, we employed fusion-evaporation reactions induced by projectiles from ^{35}Cl to ^{48}Ti on isotopically enriched Sm targets, in particular, ^{144}Sm and ^{147}Sm; targets of ^{151}Eu, ^{153}Eu and ^{nat}Eu were also used. Bombarding energies were close to the fusion barrier. The experiments were carried out by using the technique described in [3]. Until now 13 different reactions were tried out in searching for delayed fission effects in this nuclear region. The most

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For producing very proton-rich nuclei in the region of Hg - Pb, we employed fusion-evaporation reactions induced by projectiles from ^{35}Cl to ^{48}Ti on isotopically enriched Sm targets, in particular, ^{144}Sm and ^{147}Sm; targets of ^{151}Eu, ^{153}Eu and ^{nat}Eu were also used. Bombarding energies were close to the fusion barrier. The experiments were carried out by using the technique described in [3]. Until now 13 different reactions were tried out in searching for delayed fission effects in this nuclear region. The most noticeable effect was repeatedly observed in the reaction $^{144}Sm+^{40}Ca$, where some 600 delayed fission events were detected as a result of five irradiations with the total ^{40}Ca beam dose of $3.5\cdot10^{18}$ particles. The half-life of this fission activity was determined to be $0.97^{+0.09}_{-0.08}$ s*), whereas its yield was found to correspond to the cross section $\sigma_{df}\approx60\pm30$ pb. The 0.97-s fission activity was not seen in the ^{40}Ca-induced reactions on targets of ^{147}Sm, ^{150}Sm and ^{154}Sm; in irradiating ^{144}Sm by ^{35}Cl and ^{40}Ar projectiles it was not revealed either. In all of the above reactions, the yields of any fission events with $T_{1/2}\geq0.1$ s decrease by 10 to 100 times as compared to the $^{144}Sm+^{40}Ca$ case. As argued in [3], the most probable origin of the 0.97-s fission activity seems to be the ECDF occurring in the decay chain $^{180}Tl\xrightarrow[0.97\ s]{EC(\beta^+)}{}^{180}Hg$. For this chain, the ECDF probability [2,3] was estimated to be $P_{df}\approx3\cdot10^{-(7\pm1)}$. Experiments are now under way to identify via α and $EC(\beta^+)$ decay the still unknown, extremely proton-rich precursor ^{180}Tl by applying a new IGISOL technique [5] at SARA in Grenoble.

In further experiments, a significant ECDF effect with $T_{1/2}=0.40^{+0.08}_{-0.06}$s was found in the $^{147}Sm+^{45}Sc$ reaction where 140 fission events were detected after applying the ^{45}Sc beam dose of $2.6\cdot10^{18}$; the corresponding σ_{df} value is 40±20 pb. More prolific turned out to be the $^{153}Eu+^{40}Ca$ reaction where 253 fission events with $T_{1/2}=0.29^{+0.03}_{-0.02}$ s were detected as a result of a bombardment with the ^{40}Ca beam dose of $1.0\cdot10^{18}$; this corresponds to $\sigma_{df}\approx100\pm50$ pb. The fission activity with $T_{1/2}=0.33^{+0.05}_{-0.04}$ s was detected also in the $^{nat}Eu+^{40}Ca$ reaction; besides, it was observed in the reaction $^{151}Eu+^{40}Ca$. Finally, a fission activity with $T_{1/2}=0.32^{+0.12}_{-0.07}$s and $\sigma_{df}\approx15\pm10$ pb was revealed in irradiating ^{144}Sm by ^{48}Ti projectiles. At the same time, no fission activity with $T_{1/2}\approx0.3$ s was found in the reactions $^{144}Sm+^{45}Sc$ and $^{147}Sm+^{48}Ti$. An analysis of the whole evidence suggests that the ECDF activity with $T_{1/2}\approx0.3$ s produced by the reactions $^{153}Eu+^{40}Ca$, $^{151}Eu+^{40}Ca$, $^{nat}Eu+^{40}Ca$, $^{147}Sm+^{45}Sc$, and $^{144}Sm+^{48}Ti$ is associated with the decay chain $^{188}Bi\xrightarrow[0.3\ s]{EC(\beta^+)}{}^{188}Pb$ (see also [3]).

The discovery of ECDF of ^{180}Hg and ^{188}Pb has given good reasons for extending searches for this phenomenon to proton-rich nuclides of the heavier elements ranging from Po to Th. To advance in this direction, we have performed a series of experiments involving fusion-evaporation reactions of two different kinds. At first targets of ^{144}Sm and ^{147}Sm were

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*) Please note that all half-life values reported in the present paper were deduced by the maximum likelihood method [4]. The indicated errors of the half-lives reflect statistical uncertainties only.

bombarded by ^{52}Cr, ^{56}Fe and ^{58}Ni beams. In this part of the work, 7 different reactions were tried out. Although in some cases rare delayed fission events have in fact been detected, it is rather difficult to characterize these effects because of very low yields. Fusion-evaporation reactions of this kind produce extremely proton-rich, α-decaying nuclides whose ground-state properties remain still to be completely unknown. Also, strong dynamic limitations to fusion can be expected to arise in the Sm+Fe and Sm+Ni reactions. Therefore a more promising way of producing appropriate proton-rich species may be associated with the use of more asymmetric target-projectile systems involving, e.g., targets of rare-earth nuclides, Tb through Yb, and beams of ^{40}Ca or ^{40}Ar.

To explore this possibility, we irradiated targets of ^{159}Tb, ^{165}Ho and ^{169}Tm by 240-MeV ^{40}Ca projectiles. A significant delayed fission effect was observed only in the ^{159}Tb+^{40}Ca case. As a result of three irradiations with the total ^{40}Ca beam dose of $1.4\cdot10^{18}$, we have detected 148 fission events distributed in time according to a half-life of $0.23^{+0.05}_{-0.03}$ s. The σ_{df} value was estimated to be 45±20 pb. An explanation of the effect observed can be associated with ECDF in the decay chain $^{196}\mathrm{At}\xrightarrow[0.23\ \mathrm{s}]{\mathrm{EC}(\beta^+)}{}^{196}\mathrm{Po}$. To make a more definite assignment of the 0.23-s activity, further experimental work is called for. Yet the very fact of observing the third ECDF case in the preactinide region seems to be beyond any doubt.

In fact, our experimental results mean that, exemplified by the ECDF process, a new region of low-energy fission exists far outside the traditional one represented by transuranic species. Potentially, this finding offers a variety of interesting studies aimed at exploring the pattern of low-energy fission of the relatively light nuclei near the proton drip line.

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