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On the Properties of the Element 106 Isotopes Produced in the Reactions Pb + ^{54}Cr

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In ^{54}Cr ion bombardments of targets prepared from enriched lead isotopes the spontaneous fission probability for the isotopes of element 106 formed in the reactions Pb(^{54}Cr, 1, 2n)106 was investigated. The spontaneous fission half-life of the doubly-even isotope ^{260}106 has been shown to be $T_{SF} \gtrsim 5$ ms. The half-lives of neighbouring odd-mass isotopes have also been estimated: $T_{SF}(^{259}106) \gtrsim 0.1$ s and $T_{SF}(^{261}106) \gtrsim 0.4$ s. The results of the experiments are discussed in comparison with the latest theoretical calculations.

In connection with experiments to synthesize element 108 some data are necessary on properties of isotopes with $Z=106$ which can be produced as a result of the α-decay of the $Z=108$ nuclides. The nuclear stability itself of element 106 against spontaneous fission (lifetimes T_{SF}) presents also interest in view of a sharp change in the T_{SF} systematics for $Z=104$. For comparison with theory, doubly-even isotopes with $Z \geqq 104$ (primarily $Z=106$) are most informative since for these nuclei the uncertain hindrance factor for T_{SF} due to oddness is absent. The T_{SF} data for isotopes of element 106 are rather scarce, they concern only the odd-mass isotopes ^{259}106 [1] and ^{263}106 [2]. In our experiments to search for spontaneously fissioning isotopes with $Z=106$, carried out in 1974, we used the "cold fusion" reactions Pb + ^{54}Cr which are most suitable because of the low excitation energy of the compound nucleus ($E^*_{min} \approx 19$ MeV). In bombardments of the lead isotopes ^{206,207,208}Pb by ^{54}Cr ions of wide range energies up to 290 MeV we detected two spontaneous fission activities with sharply different half-lives: in millisecond (4–10 ms) [1] and second ($\sim$1.5 s) [3] ranges.

As a result of a series of control experiments and cross bombardments it was unambiguously established that the activities are both due to isotopes of element 106. The long-lived activity was identified to be the isotope ^{255}104 (the spontaneous fission probability $b_{SF} \approx 50\%$) formed as a result of ^{259}106 α-decay, and this allowed one to establish the considerable α-decay probability for this isotope of element 106 [3]. The short-lived activity might be due to the isotopes ^{259}106 or ^{260}106. However, the theoretically predicted [4] lifetime T_{SF} (^{260}106) had to be two orders of magnitude smaller than the known value of T_{SF} ($^{258}_{154}$104) [5], i.e. to be $\sim$0.1 ms, which could not be observed in our experiments. The then available data on the probability of neutron emission in "cold fusion" experiments also indicated the most probable value $A=259$[1].

With the construction of the U400 accelerator, the intensity of Ti, Cr, Mn and Fe ion beams increased by several tens of times. Having improved the experimental technique to adjust it to the increased beam intensity and having at our disposal lead isotopes with higher enrichment we turned again to the study of the reactions Pb + ^{54}Cr with the aim of determining in more detail the properties of both the odd-mass and doubly-even isotopes of element 106. The performance of the experiments was similar to that described earlier, and it allowed one to reach the maximum sensitivity in detecting spontaneously fissioning reaction products [1, 3]. A wide range of half-lives, from 10^{-3} to 10^{2} s, was investigated in 290 MeV ^{54}Cr ion bombardments of targets pre-

[1] Later additional data were obtained by Münzenberg et al., who showed that the one-neutron emission channel is very likely to take place [6]

Table 1. Experimental results

Mass number of Pb target	Enrichment, %	Number of detected fragment tracks	Observed activities			
			$T_{\frac{1}{2}}=1.5$ s		$T_{\frac{1}{2}}=6$ ms	
			W_{SF} yield $\times 10^{-16}$ per ion	σ_{est}[a] production cross section $\times 10^{-34}$ cm^2	W_{SF} yield $\times 10^{-16}$ per ion	σ_{est}[a] production cross section $\times 10^{-34}$ cm^2
206	96	165	5.6	4	$\lesssim 1.5$	$\lesssim 0.5$
207	93	125	6.0	4	8.8	3
208	98	416	$\lesssim 0.4$	$\lesssim 0.3$	12.5	4

[a] σ_{est} is an estimate of production cross sections for the isotopes ^{259,260}106 in the maximum of excitation functions of the reactions Pb(^{54}Cr, xn) for the thickness of the target effective layer corresponding to an ion energy loss of 10 MeV

pared from the enriched isotopes ^{206,207,208}Pb. In those experiments we again observed the two activities with $T_{\frac{1}{2}}=6^{+2}_{-1}$ ms and $T_{\frac{1}{2}}=1.5^{+0.3}_{-0.2}$ s. The values of half-lives and yields of these activities agree with those measured earlier [1, 3].

At the same time, owing to large statistics (a total of about 700 spontaneous fission fragments have been detected) one succeeded in clarifying the correlation between the yields of these activities with target mass numbers. The 1.5 s activity is equally likely to be formed in reactions on ^{206,207}Pb targets and is not observed in the reaction ^{208}Pb+^{54}Cr in which its yield decreases by at least a factor of 15. The 6 ms activity is formed with the same probability in reactions on ^{207,208}Pb targets, whereas in the reaction ^{206}Pb+^{54}Cr its yield decreases by a factor of more than 5 (Table 1). Hence it follows that the activities observed belong to *different* isotopes of element 106.

As previously, the 1.5 s activity should be assigned to the isotope ^{255}104, a product of ^{259}106 α-decay, which is expected to be formed with the maximum yield in the reactions ^{206,207}Pb(^{54}Cr, 1, 2n)^{259}106.

The decrease in the yield of this activity in the reaction ^{208}Pb+^{54}Cr corresponds to the relatively low probability for the channel involving the emission of 3 neutrons, as has already been observed in the reactions Pb+^{50}Ti [6].

The 6 ms activity should be attributed to the isotope ^{260}106, which has a maximum yield in the reactions ^{207,208}Pb(^{54}Cr, 1, 2n)^{260}106 and a smaller yield in the radiation-capture reactions ^{206}Pb(^{54}Cr, γ)^{260}106. In our view, this conclusion is essential since in this case $T_{SF}(^{260}_{154}106)$ turns out to be comparable to $T_{SF}(^{258}_{154}104)$ and needs a detailed consideration.

First of all we would like to note that the measured yield of the 6 ms spontaneous fission activity corresponds to the expected yield of the isotope ^{260}106 from the reactions ^{207,208}Pb(^{54}Cr, 1, 2n)^{260}106. This follows from a comparison with the similar reactions Pb+^{50}Ti leading to the formation of the known isotopes ^{255}104 and ^{256}104 ($b_{SF}\approx 100\%$). For example

$$W[^{208}\text{Pb}(^{54}\text{Cr}, 2n)^{260}106\,(6\text{ ms})]/$$
$$W[^{207}\text{Pb}(^{54}\text{Cr}, 2n)^{259}106\,(1.5\text{ s})]\approx$$
$$W[^{208}\text{Pb}(^{50}\text{Ti}, 2n)^{256}104]/$$
$$W[^{207}\text{Pb}(^{50}\text{Ti}, 2n)^{255}104]=2.1\pm 0.7.$$

Here W is the isotopic yield measured by detecting spontaneous fission events. The absence, in the reaction ^{206}Pb+^{54}Cr, of any activity with $T_{\frac{1}{2}}$ in the range 2×10^{-3} s − 10 s, apart from the 1.5 s activity, indicates that the α-decay probability for the isotope ^{259}106 is close to 100%. Thus from the relation given above it follows that the 6 ms activity yield corresponds to the total yield from the reaction ^{208}Pb(^{54}Cr, 2n)^{260}106. This is a ground for eliminating the assumption that

$$T_{SF}(^{260}106)\lesssim T_{\alpha}(^{260}106)<1\text{ ms}$$

since in this case a considerable number of spontaneous fission events in ^{260}106 might remain unobserved in our experiments.

Following the systematics, the partial half-life T_{α} (^{260}106) is equal to ~3 ms [7], and the value of $T_{\frac{1}{2}}=6$ ms practically does not differ from the half-life of ^{256}104, the daughter product of ^{260}106 α-decay ($5.2^{+1.8}_{-1.2}$ ms according to our data, $8.1^{+1.6}_{-1.1}$ ms following Münzenberg et al. [6]). Thus the α-decay probability for the isotope ^{260}106 can turn out to be predominant[2]. In this case the time distribution of

[2] For the isotopes $^{258-262}$106 the β-decay (electron capture) probability is negligibly small [7]

spontaneous fission fragments in producing ^{260}106 should have the characteristic form of a curve with an activity buildup.

We carried out experiments with the aim of checking this hypothesis using, with different time regimes, the reaction ^{208}Pb + ^{54}Cr which yields a minimum of the long-lived activity. Figure 1 shows the total time distribution of the tracks detected in those experiments. The initial part of the distribution is characterised by some deviation from the one-component decay curve and this deviation exceeds the statistical error. The analysis of this distribution assuming the two-component "buildup-decay" curve shows that if the α-decay probability of ^{260}106 is $b_\alpha > 80\%$, its half-life then is $T_{\frac{1}{2}}(^{260}106) = 2.5 \pm 1.5$ ms.

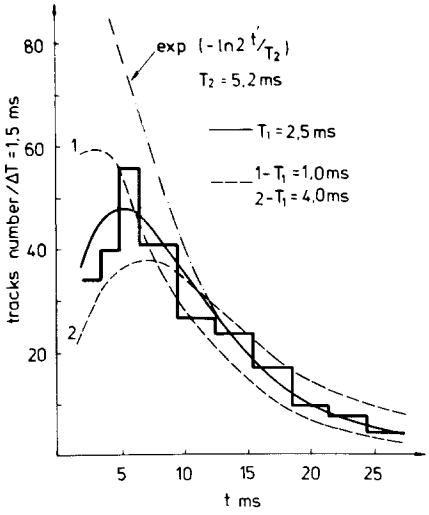

Fig. 1. The time distribution of the spontaneous fission fragments detected in the reaction ^{208}Pb + ^{54}Cr. The curves present the distributions calculated for the case of producing the isotope ^{256}104 ($T_{\frac{1}{2}} = T_2$) as a result of ^{260}106($T_{\frac{1}{2}} = T_1$) α-decay

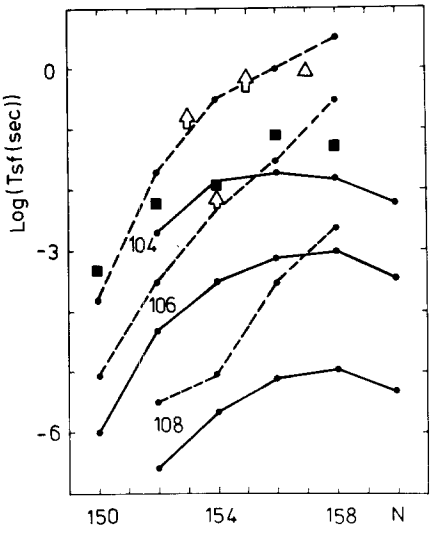

Fig. 2. The T_{SF} values for doubly-even ($Z = 104$, 106 and 108) and even-odd ($Z = 106$) nuclei. ——— calculations of Randrup et al. [4]; – – – calculations of Baran et al. [8]; ■— known experimental data for $Z = 104$, △—^{263}106 [2]; ⇧— present paper

One can apparently choose the optimal time regime of observation and obtain more accurate data by increasing statistics. However, despite the accurate $T_{\frac{1}{2}}(^{260}106)$ values and the branching ratio of this isotope its spontaneous fission half-life $T_{SF} \gtrsim 5$ ms.

It is also possible to make some conclusions about T_{SF} of the odd-mass isotopes ^{259,261}106. According to systematics, the α-decay half-lives of these isotopes are equal to 0.2 and 0.08 s, respectively [7].

The absence of a noticeable spontaneous fission effect which could be attributed to these isotopes produced in the reactions ^{206}Pb(^{54}Cr, n)^{259}106 and ^{206}Pb(^{54}Cr, n)^{261}106 enables one to establish that $T_{SF}(^{259}106) \gtrsim 0.1$ s and $T_{SF}(^{261}106) \gtrsim 0.4$ s.

In Fig. 2 the obtained data are compared with the T_{SF} calculations for doubly-even nuclei [4, 8]. It should be noted that our T_{SF} values for ^{260}106 agree with the results of Baran et al., who however overestimated the T_{SF} value for ^{258}104. Is the relative enhancement of stability against spontaneous fission, observed for $Z = 106$ and $N = 154$, reserved for a wider range of nuclei with $Z \geqq 106$? To answer this question, some information about other double-even isotopes of elements 106 and 108 seems to be needed.

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