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On the Stability of the Nuclei of Element 108 with $A=263$–265

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In bombarding ^{209}Bi and ^{207,208}Pb targets by ^{55}Mn and ^{58}Fe ions the yields of "cold fusion" reactions have been determined using a sensitive technique for detecting $T_{\frac{1}{2}} \geqq 1$ ms spontaneous fission and the α-decay of heavy actinide elements. It has been shown that the $A=263$–265 isotopes of element 108, including the even-even isotope ^{264}108, undergo mainly α-decay. The obtained results, together with the known data on the properties of the isotopes of elements 104 and 106, provide evidence for the enhanced stability of the $Z=108$ nuclei against spontaneous fission.

It is known that the probability for heavy nuclei to decay by spontaneous fission is subject to strong variations with Z and N due to shell effects on the height and shape of the fission barrier. This fact manifests itself in a sharp change of the dependence of spontaneous fission half-lives T_{SF} on the neutron number as one goes from $Z=102$ to $Z=104$. The experiments to study the properties of the element 106 isotopes with $N=153$–155 and 157 have demonstrated that these isotopes are α-emitters, i.e. they are rather stable against spontaneous fission [1–3]. It is of considerable interest to determine the properties and, in particular, the ratio between the main decay modes for the heavier nuclides and element 108 in the first place.

The element 108 isotopes can be produced in "cold fusion" reactions by bombarding Pb and Bi targets with ^{55}Mn and ^{58}Fe ions[1]. The mechanism of the complete-fusion reactions leading to the formation of heavy compound nuclei with $Z^2/A \gtrsim 40$ under the conditions of a strong Coulomb interaction in the entrance channel ($Z_1 Z_2 \gtrsim 2{,}000$) was investigated both experimentally and theoretically [4, 5]. As a result of the strong decrease of the compound nucleus formation probability with increasing $Z_1 Z_2$, the cross sections of the $(HI, 1, 2n)$ reactions leading to the formation of the isotopes of element 108 may turn out to be rather small (10^{-35}–10^{-36} cm^2).

It is possible to assume that the main decay modes of nuclei with $Z=108$ and $N=154$–157 are α-decay and spontaneous fission whereas the β-decay (electron capture) probability is negligibly low [6]. The α-decay of these isotopes of element 108 and their daughter products with $Z=106$ results in the formation of the $N=150$–153 isotopes of element 104, the radioactive properties of which are known well. Additional studies of these properties were carried out in separate experiments involving bombardments of ^{208}Pb with $^{48-50}$Ti ions. As a result of electron capture in ^{257}104 decay, the α-active isotope ^{253}Es ($T_{\frac{1}{2}}=20$ days, $E_\alpha=6.63$ MeV) is produced with $\sim 35\%$ probability. This isotope can be radiochemically separated and detected in small amounts. It has also been shown that in bombardments of Pb and Bi targets with $\leqq 5.5$ MeV/nucleon ions with $A \geqq 50$ the formation of heavy nuclei results from the decay of a compound nucleus by emitting one or two neutrons. The contributions of the (HI, pxn) and $(HI, \alpha xn)$ reactions involving charged particle emission, as well as those from mul-

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1 The results of the first experiments to synthesize ^{263}108 in the reaction Bi + ^{55}Mn are presented in [4]

Table 1.

Reaction	E_{lab}^{max} (MeV/u)	Beam dose ($\times 10^{18}$)	Number of events	Decay mode	$T_{\frac{1}{2}}$	Emitter observed	Reaction channel	Evaporation residue	Cross section (nb)
$^{208}Pb+^{50}Ti$	5.45	0.8	72	α	3d	^{253}Fm	$1n$	$^{257}104$	5
			7,440	sf	6.7 ± 0.2 ms	$^{256}104$	$2n$	$^{256}104$	5.5
			380	sf	1.7 ± 0.2 s	$^{255}104$	$3n$	$^{255}104$	0.6
$^{208}Pb+^{54}Cr$	5.5	0.5	34	α	20 d	^{253}Es	$1n$	$^{261}106$	0.3
		1.6	472	sf	6^{+2}_{-1} ms	$^{256}104$	$2n$	$^{260}106$	0.4
		0.5	16	sf		$^{255}104$	$3n$	$^{259}106$	0.02
$^{208}Pb+^{58}Fe$	5.5	3.0	3	α		^{253}Es	$1n$	$^{265}108$	0.004
		3.2	7	sf	8^{+20}_{-4} ms		$2n$	$^{264}108$	0.002
$^{207}Pb+^{58}Fe$	5.5	2.2	13	sf	6^{+5}_{-2} ms		$1n$	$^{264}108$	0.005
$^{209}Bi+^{55}Mn$	5.5	13	21	sf	$1.1^{+0.6}_{-0.4}$ s	$^{255}104$	$1n$	$^{263}108$	0.002

tinucleon transfer reactions ($\Delta A \geqq 30$) are negligibly small and can be eliminated from consideration.

Thus, with intense ion beams ($\sim 10^{13}\,p/s$) from the $U400$ cyclotron the experiments to synthesize isotopes of element 108 can be performed with fairly high sensitivity. The technique for detecting spontaneous fission events was described earlier. The observation of one spontaneous fission event corresponds to a production cross section of about $2\times 10^{-37}\,cm^2$ (Ref. 4). The determination of the yield of α-active products, ^{253}Es in this case, was done by the radiochemical separation of the Es fraction, followed by the measurements of the energy and time characteristics of the sample α-radiation. The total detection efficiency was equal to about 70 %. In observing one α-decay event due to ^{253}Es during the period $T=T_{\frac{1}{2}}(^{253}Es)=20$ days the sensitivity of this technique corresponds to the cross section of forming the primary isotope $^{265}108$, about $5\times 10^{-37}\,cm^2$.

The experimental conditions and results are listed in the table. The enriched isotopes ^{208}Pb (99,0 %) and ^{207}Pb (93,2 %) were used as target material. The experimental technique was rapid enough to allow the detection of spontaneously fissioning activities with $T_{\frac{1}{2}} \geqq 1$ ms.

From the data presented in Table 1 and from the results of control experiments it is possible to draw the following conclusions.

The observation of the isotopes $^{255}104$ and ^{253}Es indicates that the isotopes $^{263,265}108$ formed in the reactions Bi(^{55}Mn, n) Bi(^{55}Mn, n)$^{263}108$ and ^{208}Pb(^{58}Fe, n)$^{265}108$, undergo α-decay with considerable probability, this providing evidence for their high stability against spontaneous fission.

In bombarding ^{208}Pb with ^{58}Fe ions we have detected seven spontaneous fission tracks the time distribution of which corresponds to a decay with $T_{\frac{1}{2}} = 8^{+20}_{-4}$ ms. If we assign the observed effect to the spontaneous fission of the isotope $^{265}108$ produced in the reaction ^{208}Pb(^{58}Fe, n) (the α-decay chain of this isotope does not yield any spontaneously fissioning products [3]), then the comparison of the yields of spontaneous fission and ^{253}Es permits the estimate of the partial half-life $T_{SF}(^{265}108)$ [7].

It is however possible that the observed effect may be associated with the formation of the isotope $^{264}108$ in the reaction ^{208}Pb(^{58}Fe, $2n$). This case is of interest since it would mean the high stability of the even-even isotope with $Z=108$ against spontaneous fission. The study of the reaction $^{207}Pb+^{58}Fe$ allows one to answer this question unambiguously. As is seen from Table 1, the yield of the spontaneously fissioning activity increases by a factor of about 3 as one goes from ^{208}Pb to ^{207}Pb targets. This excludes the possibility of assuming the spontaneous fission of $^{265}108$ (as well as $^{263}108$) since the probability for the reactions (^{58}Fe, γ) and (^{58}Fe, $3n$) to occur is low.

Thus the spontaneously fissioning activity observed is associated with the formation of the isotope $^{264}108$ in the reactions ^{208}Pb(^{58}Fe, $2n$) and ^{207}Pb(^{58}Fe, n)[2]. The time distribution of spontaneous fission fragment tracks in the reactions $^{207,208}Pb+^{58}Fe$ does not differ from that observed in the reaction $^{208}Pb+^{54}Cr$. Bearing in mind that the expected α-decay half-life of the isotope $^{264}108$ (Ref. 6) is smaller than the value measured by detecting spontaneous fission we arrive at the rather essential conclusion that the even-even isotope $^{264}108$ undergoes mainly α-decay followed by the formation of the daughter α-emitter $^{260}106$ and the spon-

[2] It should be noted that the ratio between the channels of reactions involving the emission of one and two neutrons is nearly the same in the case of $^{265}108$ and $^{264}108$ production in the reaction $^{208}Pb+^{58}Fe$ and of $^{264}108$ production in the reactions $^{207,208}Pb+^{58}Fe$ (see Table 1)

taneously fissioning granddaughter nuclide $^{256}104$, i.e.

$$^{264}108 \xrightarrow{\alpha} {}^{260}106 \xrightarrow{\alpha} {}^{256}104\,(\mathrm{SF}).$$

This indicates that in the given decay chain the stability of nuclei with $Z=106$, 108 against spontaneous fission turns out to be comparable to (or possibly even higher than) that of the nucleus $^{256}104$.

The spontaneous fission half-lives of heavy nuclei with $Z=104$–108 exceed by a factor of 10^{15}–10^{18} the values predicted by the liquid-drop model. Such a high stability of these nuclei seems to be caused entirely by the fission barrier due to shell effects, the height and shape of which have been predicted [8] to remain almost unchanged in this region of the Z and N values. This fact leads to qualitatively new regularities in the dependence of the spontaneous fission probability on the nucleon composition of the heaviest nuclei.[3]

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[3] While the present paper was in print we received information (submitted to Zeitschrift für Physik) that Münzenberg et al. (Darmstadt, GSI) have detected three α-decay chains of the isotope $^{265}108$ ($E_\alpha=10.36$ MeV, $T_{\frac{1}{2}}=1.8$ ms) formed in the reaction $^{208}\mathrm{Pb}(^{58}\mathrm{Fe}, n)$ with a cross section of about $2\times10^{-35}\,\mathrm{cm}^2$, which does not contradict the present data within experimental errors

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