E7-2012-58

Yu. Ts. Oganessian[1], F. Sh. Abdullin[1], S. N. Dmitriev[1],
J. M. Gostic[2], J. H. Hamilton[3], R. A. Henderson[2], M. G. Itkis[1],
K. J. Moody[2], A. N. Polyakov[1], A. V. Ramayya[3], J. B. Roberto[4],
K. P. Rykaczewski[4], R. N. Sagaidak[1], D. A. Shaughnessy[2],
I. V. Shirokovsky[1], M. A. Stoyer[2], V. G. Subbotin[1],
A. M. Sukhov[1], Yu. S. Tsyganov[1], V. K. Utyonkov[1],
A. A. Voinov[1], G. K. Vostokin[1]

NEW INSIGHTS INTO THE ^{243}Am + ^{48}Ca REACTION PRODUCTS PREVIOUSLY OBSERVED IN THE EXPERIMENTS ON ELEMENTS 113, 115, AND 117. II

To be submitted to «Physical Review C»

[1]Joint Institute for Nuclear Research, RU-141980 Dubna, Russian Federation
[2]Lawrence Livermore National Laboratory, Livermore, California 94551, USA
[3]Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA
[4]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

Оганесян Ю. Ц. и др. E7-2012-58

Новые данные о продуктах реакции ^{243}Am + ^{48}Ca, ранее наблюдавшихся в экспериментах по получению элементов 113, 115 и 117. II

Нами продолжены эксперименты, нацеленные на измерение функций возбуждения реакции ^{243}Am+^{48}Ca и изучение радиоактивных свойств изотопов элемента 115, которые были начаты в 2010–2011 гг.; теперь они проводились при двух значениях энергии бомбардирующих частиц — 241 и 254 МэВ. При самой низкой энергии ^{48}Ca мы зарегистрировали семь цепочек распада ^{288}115 и три цепочки распада продукта испарения двух нейтронов ^{289}115, который также наблюдался ранее в реакции ^{249}Bk + ^{48}Ca как дочернее ядро после распада ^{293}117. При энергии пучка 254 МэВ зарегистрирована одна цепочка распада ^{287}115.

Путем измерения функции возбуждения при пяти значениях энергии установлено, что цепочки распада, суммарно тридцать одна, берущие начало от ^{288}115, действительно получены в канале реакции с испарением трех нейтронов из составного ядра ^{291}115. Радиоактивные свойства новых ядер ^{287}115, ^{288}115 и их дочерних ядер находятся в полном согласии с нашими результатами 2003 г.

Энергии α-частиц и времена распада изотопов ^{289}115, ^{285}113 и ^{281}Rg, определенные в перекрестных реакциях с двумя мишенными ядрами ^{243}Am и ^{249}Bk, находятся в согласии, что подтверждает открытие новых элементов 113, 115 и 117.

Работа выполнена в Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2012

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New Insights into the ^{243}Am + ^{48}Ca Reaction Products Previously Observed in the Experiments on Elements 113, 115, and 117. II

We continued experiments on measuring excitation functions of the reaction ^{243}Am + ^{48}Ca and investigation of radioactive properties of isotopes of element 115 that were started in 2010–2011, now at two projectile energies of 241 and 254 MeV. At the lowest energy of ^{48}Ca, we registered seven decay chains of ^{288}115 and three decay chains of the $2n$-evaporation product, ^{289}115, which was also observed previously in the reaction ^{249}Bk + ^{48}Ca as the daughter nucleus of the decay of ^{293}117. At the beam energy of 254 MeV one decay chain of ^{287}115 was detected.

Altogether thirty-one decay chains originating from ^{288}115 were established as the product of the $3n$-evaporation channel by measuring the excitation function at five excitation energies of the compound nucleus ^{291}115. The decay properties of all the newly observed nuclei ^{287}115, ^{288}115 and their descendant nuclides are in full agreement with those we measured in 2003.

The α-particle energies and decay times of the isotopes ^{289}115, ^{285}113, and ^{281}Rg produced in cross reactions with the two target nuclei ^{243}Am and ^{249}Bk agree well to provide cross bombardment evidence for the discovery of the new elements 113, 115, and 117.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2012

The present short article is a continuation of the previously published paper on the study of production and radioactive decay of the nuclei with atomic number 113, 115 and 117 [1].

After publishing the paper [1] that was submitted to «Physical Review Letters» on October 4, 2011, the experimental studies of the formation of isotopes in the reaction ^{243}Am + ^{48}Ca were continued in two phases:

• September 30 – December 11, 2011, with bombarding energy of ions $E_{\rm lab} = 241.0$ MeV (excitation energy range of the compound nuclei ^{291}115 $E^* = (34.2 \pm 2.2)$ MeV taking into account the target thickness),

• December 16, 2011 – February 27, 2012, with an energy $E_{\rm lab} = 253.8$ MeV ($E^* = (44.8 \pm 2.3)$ MeV).

The experiments were performed employing the DGFRS separator. The characteristics of the separator, setting the separator for registration of the recoils of element 115, calibrations of the detection equipment and other conditions in arranging these experiments were the same as in [1].

In summary, the results of this next stage of our experiment are the following.

1. At the lower energy of the ^{48}Ca beam, $E_{\rm lab} = 241.0$ MeV, seven long decay chains consisting of five sequential α decays that occur within a time interval of about 1 min and are terminated by spontaneous fission were detected. The total duration of the decay chain is determined by the spontaneous-fission (SF) halflife of the terminal nucleus and is about 30 h. Energies of α particles and halflives of the nuclei in these chains, as well as the energies of the fission fragments and spontaneous-fission halflife, within statistical uncertainty and energy resolution of the detectors, do not differ from the previously observed 24 decay events of ^{288}115 that is produced in the $3n$-evaporation channel of the reaction ^{243}Am + ^{48}Ca.

2. In addition to the above events, at this beam energy were also detected three short chains of the $\alpha \rightarrow \alpha \rightarrow$ SF type that last for about 30 s. Such a decay pattern is typical for the neighboring heavy isotope ^{289}115 that has been previously observed as α-decay product of ^{293}117 in the reaction ^{249}Bk(^{48}Ca,$4n$)^{293}117 (5 events) [2] and as an evaporation residue (single event) in the rare reaction channel ^{243}Am(^{48}Ca,$2n$)^{289}115 [1].

3. At higher energy of the beam of ^{48}Ca, 253.8 MeV, we observed a single long chain of five sequential α transitions that ended in spontaneous fission with a total decay time of 3.5 h. The decay properties of this chain agree well with a chain that was observed in the first experiment of 2003 also at the energy $E^* = 45$ MeV and that was attributed to the isotope ^{287}115 produced in the $4n$-evaporation channel of the reaction ^{243}Am + ^{48}Ca [3].

Thus, in the three experiments ([1, 3] and this work) aimed at the synthesis of the isotopes of element 115 in the fusion of ^{243}Am and ^{48}Ca, in the whole studied range of excitation energy, that is 31 MeV through 47 MeV, 37 decay chains of three types have been detected. Their yield normalized to beam dose of 10^{18} ions and target thickness of 10^{18} atoms/cm^2 depending on the excitation energy of the compound nucleus ^{291}115 is presented in Fig. 1.

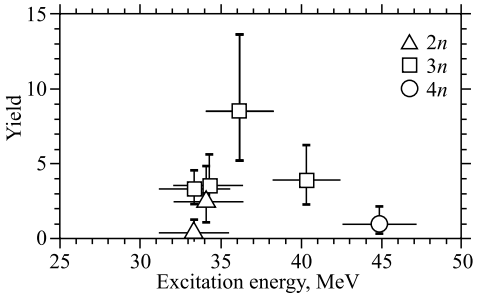

Fig. 1. Yield of the isotopes of element 115 in the reaction ^{243}Am + ^{48}Ca vs. excitation energy of the compound nucleus ^{291}115

Four events of the type $\alpha \to \alpha \to$ SF, as it could be expected for the $2n$-evaporation products, were observed only at the minimum excitation energy in the range of $E^* = 31.1{-}36.4$ MeV, in agreement with what was observed in similar reactions ^{242}Pu(^{48}Ca,$2n$)^{288}114 [4] and ^{245}Cm(^{48}Ca,$2n$)^{291}116 [5, 6].

Decay of the isotope ^{288}115, the product of the reaction ^{243}Am(^{48}Ca, $3n$)^{288}115, was detected in all 31 times. The maximum yield of this nuclide is observed at the energy $E^* = 34.0{-}38.3$ MeV close to the calculated cross section maximum of the $3n$-reaction channel. This also agrees well with the experimental data obtained in the experiments on the synthesis of the isotopes ^{287}114 and ^{290}116 in the reactions ^{242}Pu(^{48}Ca,$3n$) [4] and ^{245}Cm(^{48}Ca,$3n$) [5, 6], correspondingly.

Finally, at the maximum excitation energy we observed two identical chains that belong to the decay of the third isotope ^{287}115 that is produced in evaporation of the four neutrons from the compound nucleus ^{291}115 with excitation energy $E^* = (44.8 \pm 2.3)$ MeV.

All the three isotopes of element 115 (and, accordingly, their daughters — the isotopes of element 113) obviously differ in their decay characteristics. On the other hand, characteristics of the decay chains (energies and decay times) observed in different experiments and attributed to a given isotope do not exceed the bounds of the energy resolution of the system and statistical uncertainty of measurements. This allows us to sum up the data obtained in different experiments with the reaction ^{243}Am + ^{48}Ca and determine decay characteristics of the isotopes of element 115 more accurately.

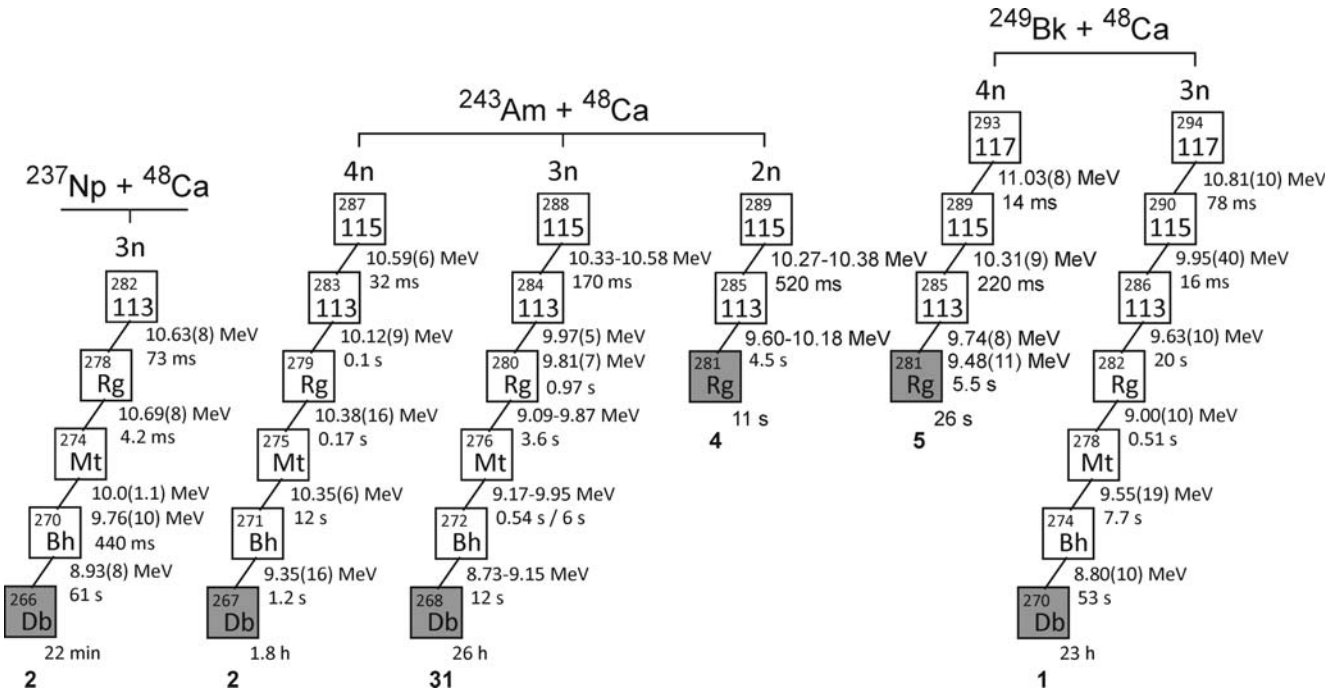

Fig. 2. Decay chains of the isotopes of elements 113, 115 and 117 observed in the reactions with ^{48}Ca (shown in Figure). The number of the detected decay events of a given isotope is shown at the bottom of the chains. For all the 23 new α emitters produced in these experiments are given the energies of the emitted α particles and the halflives. For the 5 new spontaneously fissioning nuclei — the isotopes of Db and Rg that terminate the α-decay sequences, spontaneous-fission halflives are given

In Fig. 2 are shown decay sequences of the isotopes of elements 115 and 113 produced in the reactions ^{243}Am(^{48}Ca, 2–4n)$^{289-287}$115. Also are shown decay chains of the heaviest isotope ^{290}115 (a single event) — the daughter of the isotope of element 117 synthesized in the reaction ^{249}Bk(^{48}Ca, 3n)^{294}117-α $\rightarrow$ $\rightarrow$ ^{290}115-α $\rightarrow$ ^{286}113(20 s)-α $\rightarrow$ ... [2] and a light isotope of element 113, the 0.07-s ^{282}113, product of the reaction ^{237}Np(^{48}Ca,3n) [7].

Decay of the isotope ^{289}115 is presented twice; first as a product of the reaction ^{243}Am(^{48}Ca, 2n)^{289}115, and again as α-decay daughter of the isotope of element 117 synthesized in the reaction ^{249}Bk(^{48}Ca,4n)^{293}117-α $\rightarrow$ ^{289}115. The conclusion that in the both considered cases one and the same nuclide ^{289}115 is formed is based on the similarity of the decay patterns and radioactive properties of all the three detected nuclei.

Properties of the nuclei belonging to the decay chains of the isotopes of elements 115 and 113 produced in the reactions with ions of ^{48}Ca are given in Table 1.

Table 1. Decay properties of nuclei

Z	N	A	No. observed [a]	Decay mode	Halflife [b]		E_α (MeV)	
					2012	2003	2012	2003
117	177	294	1 (1/1)	α	78^{+370}_{-36} ms		10.81±0.10	
	176	293	5 (5/5)	α	14^{+11}_{-4} ms		11.03±0.08	
115	175	290	1 (1/1)	α	16^{+75}_{-8} ms		9.95±0.40	
	174	289	9 (7/7)	α	390^{+280}_{-120} ms		10.25-10.54	
	173	288	31 (26/27)	α	171^{+42}_{-28} ms	87^{+105}_{-30} ms	10.33-10.58	10.46±0.06
	172	287	2 (2/2)	α	32^{+58}_{-13} ms	32^{+155}_{-14} ms	10.59±0.06	10.59±0.09
113	173	286	1 (1/1)	α	20^{+94}_{-9} s		9.63±0.10	
	172	285	9 (8/8)	α	$4.9^{+2.7}_{-1.3}$ s		9.48-10.18	
	171	284	31 (23/27)	α	$0.97^{+0.25}_{-0.17}$ s	$0.48^{+0.58}_{-0.17}$ s	9.97±0.05 9.81±0.07	10.00±0.06
	170	283	2 (1/1)	α	100^{+490}_{-45} ms	100^{+490}_{-45} ms	10.12±0.09	10.12±0.09
	169	282	2 (2/2)	α	73^{+134}_{-29} ms		10.63±0.08	
111	171	282	1 (1/1)	α	$0.51^{+2.5}_{-0.23}$ s		9.00±0.10	
	170	281	9 (8/-)	SF	19^{+10}_{-5} s			
	169	280	31 (25/27)	α	$3.6^{+0.9}_{-0.6}$ s	$3.6^{+4.3}_{-1.3}$ s	9.09-9.87	9.75±0.06
	168	279	2 (1/2)	α	170^{+810}_{-80} ms	170^{+810}_{-80} ms	10.38±0.16	10.37±0.16
	167	278	2 (2/2)	α	$4.2^{+7.5}_{-1.7}$ ms		10.69±0.08	

Table 1 (continued)

Z	N	A	No. observed [a]	Decay mode	Halflife [b]		E_α (MeV)	
					2012	2003	2012	2003
109	169	278	1 (1/1)	α	$7.7^{+37}_{-3.5}$ s		9.55±0.19	
	167	276	31 (27/27)	α	$0.54^{+0.14}_{-0.09}$ s 6^{+8}_{-2}	$0.72^{+0.87}_{-0.25}$ s	9.17-9.95	9.71±0.06
	166	275	2 (2/2)	α	$12^{+23.}_{-5.}$ ms	$9.7^{+46.}_{-4.4}$ ms	10.35±0.06	10.33±0.09
	165	274	2 (2/2)	α	440^{+810}_{-170} ms		10.0±1.1 9.76±0.10	
107	167	274	1 (1/1)	α	53^{+250}_{-24} s		8.80±0.10	
	165	272	31 (23/27)	α	$12.0^{+3.1}_{-2.1}$ s	$9.8^{+11.7}_{-3.5}$ s	8.73-9.15	9.02±0.06
	164	271	2 (1/1)	α	$1.2^{+5.9}_{-0.5}$ s		9.35±0.16	
	163	270	1 (1/1)	α	61^{+292}_{-28} s		8.93±0.08	
105	165	270	1 (1/-)	SF/EC	23^{+110}_{-10} h			
	163	268	51 (47/-)	SF/EC	27^{+5}_{-4} h [c]	16^{+19}_{-6} h		
	162	267	2 (2/-)	SF/EC	$1.8^{+3.3}_{-0.7}$ h	$1.2^{+5.9}_{-0.5}$ h		
	161	266	1 (1/-)	SF/EC	22^{+105}_{-10} min			

[a] Number of observed decays and in parenthesis the number of events used for calculations of halflives / α-particle energies, respectively.
[b] Error bars correspond to 68%-confidence level.
[c] The value obtained combining the results of [1, 3, 8, 9] and those of the present work.

In Table 1, together with the presently obtained data on the decay properties of the odd-Z nuclei produced in the reactions with ^{48}Ca, are given the results of the first experiment on the synthesis of the isotopes of element 115 in the reaction ^{243}Am + ^{48}Ca [3]. Comparing the presently obtained data with results of the experiment [3] in which the isotopes of elements 115 and 113 were synthesized for the first time in the reaction ^{243}Am + ^{48}Ca, we see a complete coincidence (not exceeding the bounds of the energy resolution of the detectors and statistical uncertainty of measurements) both in energies of the emitted α particles and in halflives of all the 11 nuclei that belong to the decay chains of these nuclides.

CONCLUSIONS

In the present work, in the reaction ^{243}Am + ^{48}Ca, at the energy of ^{48}Ca ions of 241 MeV, were detected three decay chains of the isotope ^{289}115 and seven chains of ^{288}115. At the beam energy of 254 MeV we detected a single decay chain of the isotope ^{287}115. The results of the experiments agree well and supplement the previously obtained data on the decay properties of the isotopes of elements 115 and 113 produced in the reaction ^{243}Am + ^{48}Ca [3].

Decay characteristics of the nuclei belonging to short $\alpha_1 \to \alpha_2 \to$ SF chains detected at the minimum excitation energy of the compound nucleus $^{291}115$ in the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$ (four events) coincide with the typical decay chain of $^{289}115$ (five events) formed as α-decay product of $^{293}117$ synthesized in the reaction $^{249}\mathrm{Bk}(^{48}\mathrm{Ca}, 4n)^{293}117$–$\alpha \to {}^{289}115$. Identification of the nuclide $^{289}115$ as the $2n$-evaporation product of the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$ links its production in the two independent cross reactions.

Identification of the isotopes of the two new elements with $Z = 115$ and 113 synthesized in 2003 in the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$, as well as the decay characteristics of the isotopes $^{287}115$ and $^{288}115$ (and accordingly of $^{283}113$ and $^{284}113$), were confirmed in full in these experiments and a cross bombardment check of the production of $^{293}117$ in the $^{249}\mathrm{Bk} + {}^{48}\mathrm{Ca}$ reaction was made.

ACKNOWLEDGMENTS

We are grateful to the JINR Directorate and U400 cyclotron and ion source crews for their continuous support of the experiment. We acknowledge the support of the Russian Foundation for Basic Research Grants No. 11-02-12050 and No. 11-02-12066. Research at ORNL was supported by the U.S. DOE Office of Nuclear Physics under DOE Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. Research at Lawrence Livermore National Laboratory was supported by LDRD Program Project No. 08-ERD-030, under DOE Contract No. DEAC52-07NA27344 with Lawrence Livermore National Security, LLC. This work was also supported by the U.S. DOE through Grant No. DE-FG-05-88ER40407 (Vanderbilt University). These studies were performed in the framework of the Russian Federation/U.S. Joint Coordinating Committee for Research on Fundamental Properties of Matter.

REFERENCES

1. *Oganessian Yu. Ts. et al.* // Phys. Rev. Lett. 2012. V. 108. P. 022502.
2. *Oganessian Yu. Ts. et al.* // Phys. Rev. Lett. 2010. V. 104. P. 142502; Phys. Rev. C. 2011. V. 83. P. 054315.
3. *Oganessian Yu. Ts. et al.* // Phys. Rev. C. 2004. V. 69. P. 021601(R).
4. *Oganessian Yu. Ts. et al.* // Phys. Rev. C. 2004. V. 70. P. 064609.
5. *Oganessian Yu. Ts. et al.* // Phys. Rev. C. 2004. V. 69. P. 054607.
6. *Oganessian Yu. Ts. et al.* // Phys. Rev. C. 2006. V. 74. P. 044602.
7. *Oganessian Yu. Ts. et al.* // Phys. Rev. C. 2007. V. 76. P. 011601(R).
8. *Dmitriev S. N. et al.* // Mendeleev Commun. 2005. V. 15. P. 1.
9. *Stoyer N. J. et al.* // Nucl. Phys. A. 2007. V. 787. P. 388c.

Received on May 22, 2012.

Редактор *Е. И. Кравченко*

Подписано в печать 24.05.2012.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,75. Уч.-изд. л. 0,5. Тираж 260 экз. Заказ № 57655.

Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/