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ALPHA DECAY OF NEW U, Np AND Pu ISOTOPES AND ALPHA SPECTROSCOPY FOR NUCLEI BETWEEN Fr AND Pa

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1. INTRODUCTION

The production and alpha-decay properties of many isotopes from Ac to Pu and their daughter products have been investigated in the late 60s and early 70s [1,2,3]. The technique used in most of these experiments allowed the determination of only the relative production rates of these isotopes. Moreover, the complexity of the alpha spectra made it very difficult to identify some of the peaks and to properly determine the line intensities. A more accurate determination of the alpha-decay properties of these nuclei with modern apparatus is presented in this paper.

In complete fusion reactions of Ne, Mg and Al ions with Tl, Pb and Bi targets nine new U-Np-Pu isotopes were synthesized and their α-decay properties were determined. In the analysis new α-lines were observed for some Fr - Pa isotopes and half-lives and line intensities were determined more precisely. This paper supersedes the preliminary results published as preprints [4-7, 14-15] or short notes [8-10], but a significant part of the results is published for the first time in this paper.

2. EXPERIMENTAL SET-UP

The experiments were performed with ^{20}Ne, ^{22}Ne, ^{26}Mg, and ^{27}Al beams from the U-400 cyclotron of the Laboratory of Nuclear Reactions, JINR, Dubna. The evaporation residues (ER) recoiling from the target were separated in-flight from projectiles and from the products of different transfer reactions by the VASSILISSA kinematic separator of complete fusion reaction products [11]. After passing through two large-area time- of flight detectors and a mylar absorber foil of 150-200 μm/cm^2, the ER are implanted into an array of silicon detector strips, where their subsequent α-decays are measured. The energy resolution of each alpha-detector strip was ≤ 25 keV (FWHM) for E_α = 7-9 MeV . The calibration error is estimated to be ± 15 keV for this energy region and ± 40 keV for E_α = 17-19 MeV, corresponding to pile-up pulses. The isotope identification was performed via recoil-α and α-α correlation analysis. Events with time spacings > 5 μs were fully resolved and with < 1 μs were fully summarized. More details about the detecting system are given in ref. [11].

3. NEW ISOTOPES

Uranium-218: This very neutron deficient isotope was produced in the reaction $^{197}Au + ^{27}Al$. Four α-α correlations were assigned to ^{218}U, all starting from α-decays at $E_{\alpha} = 8620 \pm 25$ keV, but only one α-chain is complete, i.e. the α-decay attributed to ^{218}U is followed by an α-decay of ^{214}Th and this is followed by an α-decay of ^{210}Ra. The half-life of ^{218}U is determined to be $1.5^{+7.3}_{-0.7}$ ms and the production cross section $\sigma = 1.6 \pm 1.1$ nb at a beam energy $E(^{27}Al) = 161 \pm 1$ MeV.

Uranium-223, Uranium-224: In the complete fusion reaction $^{208}Pb+^{20}Ne$ two interesting groups were found. In the time window of 200 μs the α-decays at the α-mother energy $E_{\alpha}(m) = 8470 \pm 15$ keV were found to be correlated with α-decays of the daughter nuclei $E_{\alpha}(d_1 + d_2) = 18140 \pm 40$ keV. The second correlation group at $E_{\alpha}(m) = 8780 \pm 40$ keV was identified as due to ^{223}U. The production cross section for ^{223}U was determined to be $\sigma = 0.5 \pm 0.3$ μb at a beam energy $E(^{20}Ne) = 121 \pm 2$ MeV, and $\sigma = 0.8 \pm 0.4$ μb for the other group assigned to ^{224}U, at $E(^{20}Ne) = 110 \pm 2$ MeV. More details of the data analysis are given in [10] and energies and half-lives values are shown in Tab.I .

Table 1. The characteristics of new neutron deficient isotopes synthesized at the kinematic separator VASSILISSA.

Nucl.	E_{α} keV	I_{α} %	$T_{1/2}$ ms	Ref.
^{218}U	8620 ± 25	100	$1.5^{+7.3}_{-0.7}$	
^{223}U	8780 ± 40	100	$0.018^{+0.010}_{-0.005}$	
^{224}U	8470 ± 15	100	$0.7^{+0.5}_{-0.2}$	
^{225}U	7870 ± 20	100	30^{+20}_{-10}	
	7880 ± 20	90	80^{+40}_{-20}	[13,19]
	7830 ± 20	10		
^{226}U	7570 ± 20	85 ± 5	200 ± 50	
	7420 ± 20	15 ± 5		
	7430 ± 20	100	500 ± 200	[12]
^{225}Np	8630 ± 20	100	Preliminary	data
^{226}Np	8060 ± 20	50 ± 15		
	8000 ± 20	50 ± 15		
	8044 ± 20	100	31 ± 8	[16]
^{227}Np	7680 ± 20	100 EC<25%		
	7650 ± 20		510 ± 60	[16]
	7677 ± 20			
^{230}Pu	7050 ± 20	100		

Uranium-225, Uranium-226: To synthesize ^{225}U and ^{226}U a complete fusion reaction of $^{208}Pb + ^{22}Ne$ was used. For the observed correlation at $E_m = 7570$ keV the energy and half-life of the daughter nucleus ($E_d = 7980$

keV, $T_{1/2} = 2.6 \pm 0.4$ ms) are in good agreement with the known decay characteristics of ^{222}Th. We identified this correlation as bound with the decay of ^{226}U - ^{222}Th. A supplementary argument for the identifying this result as the decay of ^{226}U is the correlation of the mother nuclei with its daughter ^{218}Ra ($E_{d1} = 8400$ keV) and grand daughter ^{214}Rn ($E_{d2} = 9050$ keV).

The isotope of ^{225}U was identified as a marked correlation between $E_m = 7870$ keV and $E_{d1} = 8150$ keV + 8470 keV (^{221}Th) and $E_{d2} = 8100$ keV (^{213}Rn). The time distribution of the correlation events for the daughter nuclei gives half-lives of 2.0 ± 0.5 ms and 20 ± 8 ms in agreement with the known half-lives of ^{221}Th and ^{213}Rn. The α-decay characteristics of ^{225}U and ^{226}U are given in Tab.I. The maximum production cross-section for ^{226}U is $\sigma \cong 5.5$ μb and for ^{225}U is $\sigma \cong 2.5$ μb.

Neptunium-225, Neptunium-226, Neptunium-227: To synthesize the new isotope ^{227}Np a complete fusion reaction $^{209}Bi + ^{22}Ne$ was used. At beam energies ranging from 106 to 115 MeV α-α correlation groups were observed with a maximum intensity at about 111 MeV between $E_m = 7680 \pm 20$ keV and $E_{d1} = 8000 \pm 20$ keV and $E_{d2} = 8200 \pm 20$ keV of ^{223}Pa and also at daughter energies of ^{219}Ac and ^{215}Fr (120 correlation events). The half-life value for daughter events $T_{1/2} = 7 \pm 1$ ms well fits to the known one for ^{223}Pa. We explain these correlation groups as due to the α-decay chain of the new isotope ^{227}Np.

The new isotope ^{226}Np we obtained in the same reaction as ^{227}Np but at a beam energy $E(^{22}Ne) = 121 \pm 1$ MeV. We observed 11+11 correlation events at α-mother energies of $E_{m1} = 8000 \pm 20$ keV and $E_{m2} = 8060 \pm 20$ keV. The daughter α-energies and half-lives are in good agreement with the known values for ^{222}Pa, ^{218}Ac and ^{214}Fr. ^{226}Np we identified also in the reaction of $^{205}Tl + ^{26}Mg$ at $E(^{26}Mg) = 142 \pm 1$ MeV. The energy and time correlation values were the same as in the case of the previous reaction. More details about these reactions are given in [9].

In the reaction of $^{209}Bi + ^{20}Ne$ two correlations were observed at α-mother energies of 8631 ± 20 keV and 8626 ± 20 keV with α-daughter energies, corresponding with known energy and half-life values of ^{221}Pa and ^{217}Ac. We suppose that these correlations may be identified as an α-decay of ^{225}Np.

The production cross section for ^{226}Np was determined to be σ = 70 ± 25 nb at E(^{20}Ne) = 121 ± 1 MeV and for ^{227}Np σ = 330 ± 150 nb at E(^{20}Ne) = 119 ±1 MeV [20].

Plutonium-230: This isotope was synthesized in the complete fusion reaction of ^{208}Pb + ^{26}Mg. ^{230}Pu was identified as the source of the correlation chain of its daughter α-decay products: 7050 ± 15 keV - 7570 ± 15 keV (^{230}Pu - ^{226}U) - 13 events; 7050 ± 15 keV - 7980 ± 15 keV (^{230}Pu - ^{222}Th) - 7 events; 7050 ± 15 keV -17400 ± 40 keV (^{230}Pu - (^{218}Ra + ^{214}Rn)) - 4 events. The energy values of these correlation groups are given in Tab.I. The measured α-decay of ^{226}U is perfectly in line with the data, obtained from the ^{208}Pb + ^{22}Ne reaction. Because of the expected half-life of ^{230}Pu (≅ 200 s) is much longer than the average time interval between recoil events in our detectors, we could not measure the half-life for this nucleus. The production cross- section for ^{230}Pu was determined to be σ = 100 nb at E(^{26}Mg) = 135 ± 1 MeV on the target. More details are given in ref. [8].

4. ALPHA SPECTROSCOPIC DATA FOR Fr - Pa NUCLEI

The use of the kinematic separator VASSILISSA and the method of recoil-α and α-α correlation analysis of experimental data allowed us, in the investigation of the above mentioned nuclear reactions to separate the alpha-active reaction products of many isotopes (^{217}Fr, ^{219,220}Ra, ^{221}Ac, $^{221-224}$Th, ^{223,224}Pa) at much better background conditions than it was possible in earlier works. As the result of such analyses we determined for some isotopes new alpha transitions, line intensity ratios and half-life values. The new data are collected and compared with earlier results in Tab.II.

5.DISCUSSION

The new experimental data on alpha-decay energies allow us to draw conclusions about the quality of several semi-empirical mass formulas. The result of the comparison is shown in Fig. The masses of known nuclei were taken from Wapstra [21]. The error bar values of experimental mass defects in Fig.1 were determined taking into consideration the experimental error

Table 2. New α-lines, line intensities, and half-lives, determined at the kinematic separator VASSILISSA.

Nucl.	E_α keV	I_α %	$T_{1/2}$ ms	E_α keV	I_α %	$T_{1/2}$ ms	Ref.
^{198m}Bi	7340 ± 30			7200 ± 20			[24]
^{217}Fr	*	100	0.016 ± 0.002	8315 ± 8	100	0.022 ± 0.005	[1]
^{219}Ra	7670 ± 20	55 ± 5	10 ± 1	7675 ± 10	65 ± 5	10 ± 3	[18]
	7980 ± 20	45 ± 5		7980 ± 10	35 ± 2		
^{220}Ra	7460 ± 20	100	17 ± 2	7457 ± 10	100	23 ± 5	[18]
^{221}Ac	7170 ± 15	2.4 ± 1		7170 ± 10	2	52 ± 2	[1]
	7380 ± 15	11 ± 2		7375 ± 10	10 ± 5		
	7440 ± 15	23 ± 4		7440 ± 15	20 ± 5		
	7650 ± 15	63 ± 7		7645 ± 10	70 ± 10		
^{221}Th	7730 ± 15	5 ± 1	1.9 ± 0.1	7733 ± 8	6	1.68	[17]
	8150 ± 15	51 ± 5		8145 ± 5	56		
	8375 ± 15	11 ± 2		8472 ± 5	39		
	8470 ± 15	33 ± 4					
^{222}Th	7980 ± 15	97 ± 1	2.2 ± 0.2	7982 ± 5	100		[18]
	7600 ± 15	3 ± 1					
^{223}Th	7290 ± 15	41 ± 5		7285 ± 10	60 ± 10	660 ± 10	[3]
	7320 ± 15	29 ± 5		7315 ± 10	40 ± 10		
	7350 ± 15	20 ± 5					
	7390 ± 15	10 ± 4					
^{224}Th	7000 ± 20	20 ± 5		7000 ± 10	19 ± 3	1050 ± 50	[3]
	7170 ± 20	80 ± 5		7170 ± 10	81 ± 3		
^{223}Pa	8000 ± 15	55 ± 4	7.5 ± 1.5	8006 ± 10	55 ± 5	6.5	[18]
	8190 ± 15	45 ± 4		8196 ± 10	45 ± 5		
^{224}Pa	7460 ± 15	25 ± 3		7490 ± 10	100	950 ± 150	[1]
	7555 ± 15	75 ± 3					

* Not determined because of partial pile-up of the pulses.

values and the error values of the daughter nuclei, taken from Ref.[21].

The Moller-Nix mass formula clearly overestimates the mass defects except for ^{218}U with closed neutron shell N = 126 (line 1).

The mass formula of Moller (line 2) gives very different values for uranium and neptunium isotopes. For neptunium isotopes with odd Z = 93 there is an excellent agreement for both odd-even and odd-odd nuclei, but for the most neutron deficient uranium isotope ^{218}U with even Z =92 and even N = 126 (closed neutron shell) the mass defect is underestimated by more than 1.5 MeV.

The difference between the experimental masses and those calculated with the Masson-Janecke formula (line 4) is more than 0.5 MeV for the most neutron deficient uranium and neptunium isotopes .

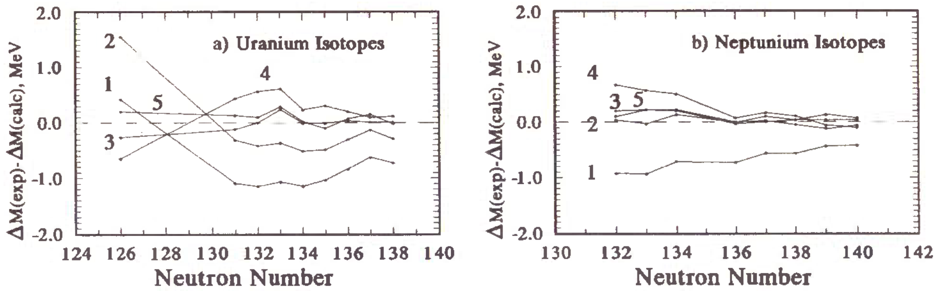

Fig. Experimental mass defects (zero level in the figure) and the predictions ($\Delta M(calc)$) of Moller-Nix (1), Moller et al. (2), Janecke-Masson (3), Masson-Janecke (4) and Liran-Zeldes (5) for the new very neutron deficient uranium (a) and neptunium (b) isotopes.

The Janecke-Masson (line 3) and Liran-Zeldes (line 5) mass formulas give excellent agreement with experimental values.

In the case of ^{227}U (N=135) the value of ΔM, based on the systematics [21], we corrected with respect to the new alpha line of ^{223}Th (7.390 ± 0.015 MeV) i.e. $\Delta M(^{227}U)$ = 28.920 ± 0.112 MeV. This value of ΔM fits better the feature of different mass formulas in this mass region. On the contrary, the value of $\Delta M(^{227}U)$ = 28.72 MeV based on the measured value of $E_\alpha(^{227}U)$ = 6.87 ± 0.02 MeV [23] is out of the lines by ≅ 200 keV.

The experimental mass defects of known isotopes and the mass defect predictions of Moller-Nix, Moller et al., Janecke-Masson, and Masson-Janecke were taken from Ref.[21] and that of Liran and Zeldes from Ref. [22].

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