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BRIEF REPORTS

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Alpha decays of light uranium isotopes

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With the use of a velocity filter, the α-particle decays of ^{224}U and ^{225}U were studied in ^{19}F bombardments of ^{209}Bi. The data obtained for these two isotopes are compared with those of previous investigators, and the α-decay rates of ^{222,224,226}U are discussed within the context of partial α half-lives for even-even nuclei with $Z \geq 84$.

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Until recently the only information available on uranium isotopes with $A < 227$ was a half-life and an α-decay energy for ^{226}U [1] and a half-life for ^{222}U [2]. We undertook a search for ^{224}U and ^{225}U α decays in ^{19}F irradiations of ^{209}Bi by using the Holifield Heavy Ion Research Facility (HHIRF) velocity filter and a detection technique described in Ref. [3]. During the course of our study the discoveries of ^{225}U [4,5], ^{224}U [6], and ^{223}U [6], and new data on ^{226}U [4] were reported. Herein, we present our results on the α-decay properties of ^{224}U and ^{225}U together with a discussion of the ^{222}U, ^{224}U, and ^{226}U decay rates and how they fit into the half-life systematics for ground-state, even-even, α-particle emitters with $Z \geq 84$.

The ^{209}B targets, 300 μg/cm^2 layers deposited on 20 μg/cm^2 carbon foils, were bombarded with 102-, 106-, and 115-MeV ^{19}F ions from the HHIRF 25-MV tandem accelerator. The first two energies were selected to maximize yields of the (^{19}F,3n) and (^{19}F,4n) products, based on available cross-section data for reactions induced by various heavy ions on nuclei in the mass region near lead. The 115-MeV energy was chosen to provide excitation-function information to assist in mass assignments. Also, some cross-bombardment data were already available from our study [7] of thorium nuclides produced in ^{16}O and ^{18}O irradiations of ^{207}Pb. Beam currents were limited to intensities of less than 500 electrical nA to minimize damage to the targets.

The magnetic and electrostatic components of the velocity filter were set so that the uranium evaporation residues recoiling out of the target at 0° were separated from the incident ^{19}F ions and other reaction products. Following separation they were implanted in a Si(Au) surface barrier detector, and their implantations provided start signals for our electronics. Except for an added capability to measure longer half-lives, the experimental setup and method have been described earlier [3]. There the half-life determination of ^{218}Ra had been done with a time-to-amplitude converter (TAC) which covered a range from about 1 to 64 μs. Since we were now searching for isotopes whose half-lives were anticipated to be in the range of 1 ms to 1 s, each observed α-decay event was tagged by a signal from a clock that was started whenever the implantation of a recoil residue occurred. Time ranges of 32 and 320 ms were used. Decay events were also recorded, as before, with the 64-μs TAC.

Figure 1 shows the spectrum recorded at an incident energy of 102 MeV during 320-ms counting intervals for α particles preceded by a residue start signal. In agreement with Hessberger *et al.* [5] we observe two α groups following ^{225}U decay. Our energy of 7879(15) keV for the more intense group agrees with values in both Refs. [4] and [5]. However, Andreyev *et al.* [4] did not observe the weaker 7821(15)-keV peak. By using decay information from both the 102- and 106-MeV experiments we determine a half-life of 95(15) ms for ^{225}U, a value which agrees with the half-life given in Ref. [5] but not with the one in Ref. [4]. The three sets of ^{225}U data are compared in Table I.

We also indicate in Fig. 1 a cluster of counts whose energy corresponds closely to the 8470-keV value assigned [6] to ^{224}U, a nuclide with a half-life of 0.7 ms. These events are emphasized in Fig. 2 where α particles observed in the same 102-MeV experiment but recorded during the first 5 ms of the 320-ms counting interval are displayed. One now sees in Fig. 2 a distinct peak whose energy, 8458(20) keV, agrees with the value of Andreyev *et al.* [6]. However, because its energy is close in value to that of one of two intense ^{221}Th α transitions, we need to consider the possibility that this peak is in reality the result of ^{221}Th decay. The energies and relative intensities

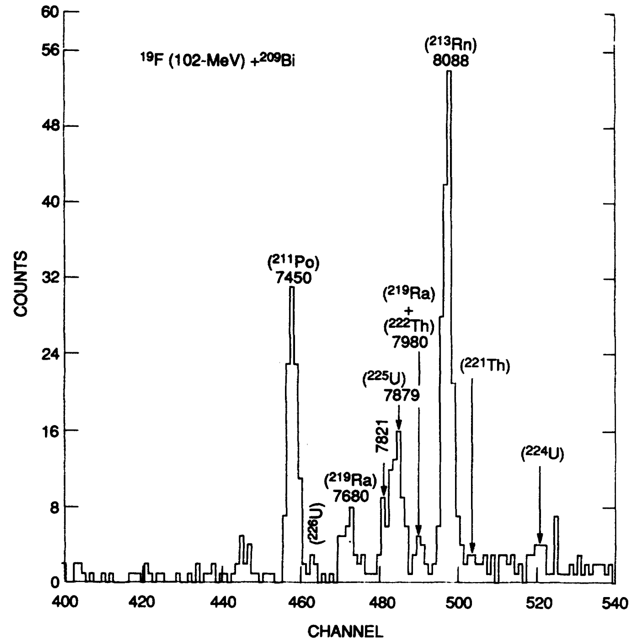

FIG. 1. α-particle spectrum measured in 102-MeV ^{19}F bombardments of ^{209}Bi during 320-ms counting intervals. Energies are expressed in keV.

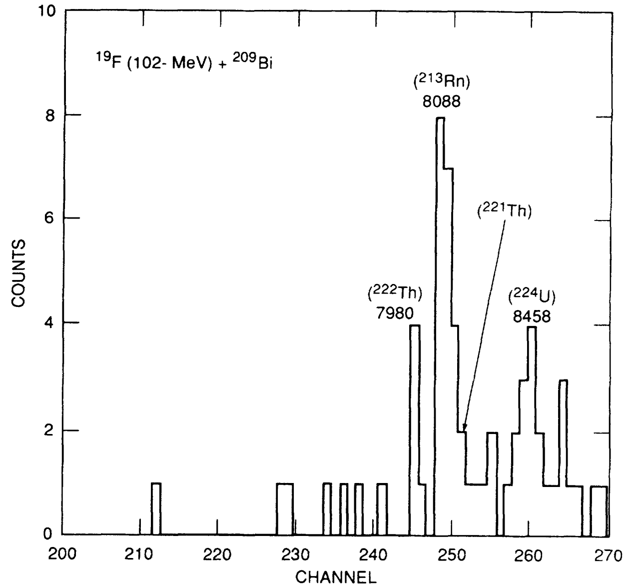

FIG. 2. α-particle spectrum measured in 102-MeV ^{19}F bombardments of ^{209}Bi during the first 5 ms of 320-ms counting intervals (see Fig. 1). Energies are expressed in keV.

of the two intense ^{221}Th α transitions are as follows: (1) 8146 keV (62%) [8] and 8145 keV (56%) [9] and (2) 8472 keV (32%) [8] and 8470 keV (39%) [9]. In both Figs. 1 and 2, the location of the stronger ^{221}Th α peak is indicated, and it is clear that most of the counts in the 8458-keV group (Fig. 2) are due to ^{224}U. Based on the combined 102- and 106-MeV data we determine a half-life of 1.0(4) ms for ^{224}U. Our ^{224}U results and those of Ref. [6] are compared in Table I.

A peak labeled ^{226}U in Fig. 1 is close to the energy of 7570(20) keV reported by Andreyev *et al.* [4] for ^{226}U. This energy is very different from the 7430(30)-keV value measured by Viola *et al.* [1]. The ^{226}U half-lives determined in these two previous investigations are also dissimilar (see Table I) and, coupled with the respective α-decay energies, lead to very different α reduced widths as we discuss later. The interested reader is referred to Ref. [4] where arguments are presented against the assignment by Viola *et al.* [1] of the 7430-keV peak to ^{226}U. Note that if the ^{226}U α-decay energy is indeed 7430 keV, then that particular α group would be obscured in Fig. 1 by the ^{211}Po 7450-keV peak.

Figure 3 shows the spectrum measured in the 115-MeV experiment during 32-ms counting cycles. There is no indication of the ^{225}U and ^{224}U α peaks so that the 115-MeV bombarding energy must be past the maxima of the (^{19}F,3*n*) and (^{19}F,4*n*) excitation functions. The α-particle spectrum gated by the 64-μs TAC at this bom-

TABLE I. Half-lives and α-decay energies of light uranium isotopes.

	Present data			Previous data			
Nuclide	E_α (keV)	I_α (%)	$T_{1/2}$ (ms)	E_α (keV)	I_α (%)	$T_{1/2}$ (ms)	Ref.
^{226}U				7570(20)	85	250^{+150}_{-100}	[4]
				7420	15		
				7430(30)	100	500(200)	[1]
^{225}U	7879(15)	85	95(15)	7880(20)	90	80^{+40}_{-20}	[5]
	7821(15)	15		7830(20)	10		
				7870(20)	100	30^{+20}_{-10}	[4]
^{224}U	8458(20)	100	1.0(4)	8470(15)	100	$0.7^{+0.5}_{-0.2}$	[6]
^{223}U				8780(40)	100	$(18^{+10}_{-5})\times10^{-3}$	[6]
^{222}U					100	$(1.0^{+1.2}_{-0.4})\times10^{-3}$	[2]

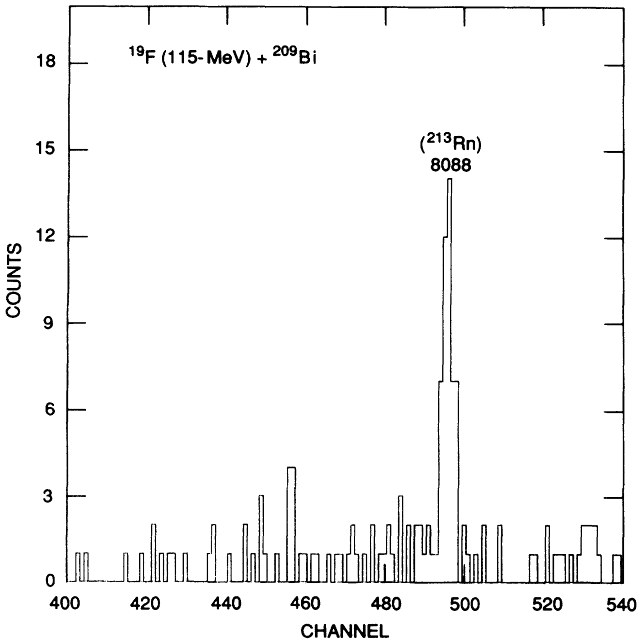

FIG. 3. α-particle spectrum measured in 115-MeV ^{19}F bombardments of ^{209}Bi during 32-ms counting intervals. Energies are expressed in keV.

barding energy was also examined. The 8780-keV peak assigned to ^{223}U by Andreyev *et al.* [6] was not seen even though the nuclide's 18-μs half-life (Table I) would place its decay events within the TAC range. For this ^{228}U compound system there is apparently a large amount of fission competition at each evaporation step, so that the (^{19}F,5n) reaction cross section must be substantially smaller than that for the (^{19}F,4n) reaction.

Figure 4 displays a plot of reduced widths as a function of neutron number for ground-state-to-ground-state α transitions of even-even elements with $Z \geq 84$. In this discussion Rasmussen's α-decay formalism [10] was used to calculate the width δ^2, which is defined as $\delta^2 = \lambda h / P$, where λ is the decay constant, h is Planck's constant, and P is the α-particle penetrability factor. As noted many times previously, widths for these s-wave transitions vary regularly with nucleon number so that discontinuities such as the one at $N=126$ (and $N=152$) indicate shell closures.

The δ^2 values calculated for ^{226}U with the data of Refs. [1] and [4] are 0.30 and 0.17 MeV, respectively. While the first width appears to be too large for an $N=134$ nucleus (particularly with $Z=92$), the 0.17-MeV value fits within the trends observed in Fig. 4. Our ^{224}U data and those of Ref. [6] yield δ^2 values of 0.095 and 0.125 MeV, respectively. Since both widths fit the systematics, we show their average in Fig. 4. Hingmann *et al.* [2] reported a 1-μs half-life (Table I) for ^{222}U but were not able to measure the nuclide's α-decay energy. In their discussion they noted that this short half-life necessitated a decay energy of 9.66 MeV if the reduced width of ^{222}U were to be consistent with values of other even-even nuclei in this mass region. According to the authors [2] this energy is about 0.45 MeV greater than what one would expect from systematics. The ^{224}U decay energy is now known, and by using it and the 7570-keV value of Andreyev *et al.* [4] for ^{226}U one can extrapolate to ^{222}U and deduce its energy to be about 9.33 MeV. A δ^2 value of 0.49 MeV is then calculated for ^{222}U; based on the widths shown in Fig. 4, this value is clearly too large. To obtain a width of 0.15 MeV a decay energy of 9.55 MeV is required. However, since there are no irregularities observed in plots of decay energy vs neutron number for Th, Ra, and Rn nuclei for N between 130 and 140, a more likely resolution is that the half-life of ^{222}U is closer to the upper limit of 2.2 μs (Table I) set by Hingmann *et al.* [2].

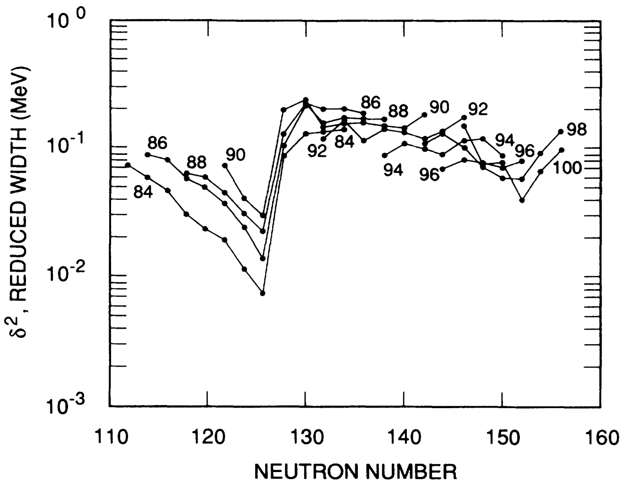

FIG. 4. Reduced widths plotted as a function of neutron number for s-wave α transitions for elements with $Z \geq 84$.

In the 1986–1987 atomic mass predictions [11] Wapstra, Audi, and Hoekstra [12] list masses deduced mainly from experimental data. Values for uranium nuclei with $A < 226$ are not in their compilation, but now that the α-decay energies of ^{223}U, ^{224}U, and ^{225}U are available, the uranium masses can be calculated because those of ^{219}Th, ^{220}Th, and ^{221}Th are listed [12]. Since uncertainties in the α-decay schemes of nuclei that are not doubly even can lead to masses with large error bars (see Ref. [12]), we prefer to leave the mass determination of ^{223}U and ^{225}U to those who deal in global surveys. For ^{224}U, however, based on an α-decay energy of 8464 keV (average of measurements in our work and in Ref. [6]) and a 14.647-MeV mass excess [12] for ^{220}Th, the ^{224}U mass excess is calculated to be 25.689 MeV with an uncertainty of about 30 keV. Finally, if the ^{226}U decay energy is 7570 keV, then the isotope's mass excess is 27.312 MeV rather than the 27.170-MeV value [12] deduced from the α-decay data of Ref. [1].

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