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Decay properties of the new isotopes ^{172}Hg and ^{173}Hg

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The α decays of the two neutron-deficient nuclei ^{172}Hg and ^{173}Hg were observed for the first time using the ^{78}Kr(^{96}Ru,2n) and ^{80}Kr(^{96}Ru,3n) reactions, respectively. The reaction products were dispersed according to their mass-to-charge state ratios in the Argonne Fragment Mass Analyzer and implanted in a double-sided silicon strip detector, where their subsequent decays were studied using spatial and time correlations between implants and decays. A half-life of $250(^{+350}_{-90})$ μs and an energy of 7350(12) keV were deduced for the α decay of ^{172}Hg. In ^{173}Hg the half-life was measured to be $0.93(^{+0.57}_{-0.26})$ ms and the corresponding energy is 7211(11) keV. In addition, the half-life and energy of the α decay of ^{174}Hg were measured more precisely. The reduced widths deduced for these Hg isotopes indicate that the observed decays correspond to unhindered $\Delta l=0$ transitions. The α-decay Q values are compared with the values calculated using mass tables by Möller and Nix, and by Liran and Zeldes. The latter mass tables show better agreement with the data. [S0556-2813(99)50409-3]

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Within the last several years, a wealth of new information on nuclei located at and beyond the proton drip line has become available in the region of the nuclidic chart between the closed proton shells $Z=50$ and $Z=82$. Much of this work has been directed at the identification of new proton emitters in odd-Z nuclei ranging from ^{131}Eu ($Z=63$) to ^{185}Bi ($Z=83$) [1]. In addition, studies of the α-decay properties of proton-rich nuclei has yielded complementary information on nuclei lying at the edges of stability. For example, measurements of α-decay energies and lifetimes far from the line of stability represent one of the means to discriminate between different mass formulas. The growing uncertainty of different models when moving towards the proton-drip line is reflected in an increasing spread of predicted masses and α-decay Q values.

In this Rapid Communication, we report on the identification of the two new isotopes ^{172}Hg and ^{173}Hg by their respective α decays. In addition, the half-life and energy of the α decay of ^{174}Hg have been measured with higher precision. Prior to this work ^{174}Hg was the lightest known Hg isotope [2]. It should also be noted that there has also been renewed interest in the study of excited states in the light Hg isotopes. Recent measurements have examined the evolution of shape-coexistence between the near-spherical ground state and the excited well-deformed prolate structure in ^{176,178}Hg [3,4]. In addition, Nilsson-Strutinsky calculations predict that the light Hg isotopes ($N\leqslant 98$) should exhibit an excited superdeformed minimum with $\beta_2=0.5-0.56$ [5] which could be populated at high spins.

The light isotopes of Hg studied in this work were produced using beams of ^{78}Kr and ^{80}Kr, from the ATLAS superconducting linear accelerator at Argonne National Laboratory, impinging on a 0.4 mg/cm^2 thick ^{96}Ru isotopically enriched target. The ^{96}Ru target was placed on a 0.7 mg/cm^2 thick Al backing, which faced the beam during the experiment. The ^{78}Kr(^{96}Ru,2n) reaction at a beam energy of 375 MeV was used to produce ^{172}Hg, while ^{173}Hg was populated in the ^{80}Kr(^{96}Ru,3n) reaction at a beam energy of 400 MeV. Using the same beam-target combination, but a lower beam energy of 375 MeV, ^{174}Hg was populated via the two-neutron evaporation channel. The summary of the reactions used in the present work is shown in Table I.

Evaporation residues from the fusion reactions listed above were separated from the beam and dispersed according to their mass-to-charge state ratio (M/Q) using the Argonne

TABLE I. The properties of the light Hg isotopes studied in the present work. The cross sections were estimated assuming a 10% FMA efficiency. A screening correction of 29.7 keV was added to the deduced α-decay Q values. The half-lives ($t_{1/2}^{\mathrm{Rasm}}$) and reduced widths (δ^2) were calculated using the prescription of Rasmussen [12]. Further details are given in the text.

Reaction	E^*_{CN} [MeV]	σ [nb]	E_α [keV]	Q_α [keV]	$t_{1/2}$ [ms]	$t_{1/2}^{\mathrm{Rasm}}$ [ms]	δ^2 [keV]
^{96}Ru(^{80}Kr,2n)^{174}Hg	37	330	7066(8)	7262(8)	$1.9^{+0.4}_{-0.3}$	2.4	92(17)
^{96}Ru(^{80}Kr,3n)^{173}Hg	50	15	7211(11)	7411(11)	$0.93^{+0.57}_{-0.26}$	0.86	67(25)
^{96}Ru(^{78}Kr,2n)^{172}Hg	36	9	7350(12)	7555(12)	$0.25^{+0.35}_{-0.09}$	0.33	96(55)

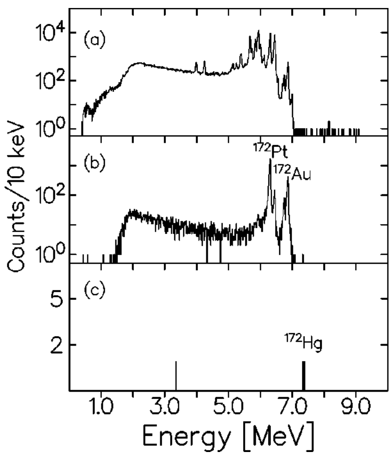

FIG. 1. Energy spectra of α particles measured in the DSSD using the ^{96}Ru+^{78}Kr reaction at 375 MeV: (a) all decays; (b) decays following mass 172 residues within 40 ms; (c) decays followed by 6.83 MeV ^{168}Pt α particles within 100 ms.

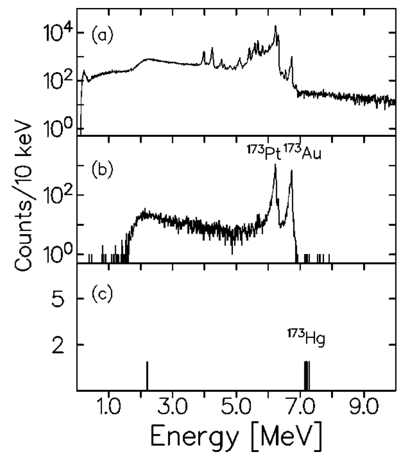

FIG. 2. Energy spectra of α particles measured in the DSSD using the ^{96}Ru+^{80}Kr reaction at 400 MeV: (a) all decays; (b) decays following mass 173 residues within 40 ms; (c) decays followed by 6.7 MeV ^{169}Pt α particles within 100 ms.

Fragment Mass Analyzer (FMA) [6]. After passing through a position sensitive parallel grid avalanche counter (PGAC) placed at the focal plane of the FMA for the M/Q measurement, the residues were implanted into a double-sided silicon strip detector (DSSD) placed about 40 cm behind the focal plane. The front and back surfaces of the 4×4 cm^2, 60 μm thick DSSD were each divided into 40 strips. The front and back strips were orthogonal to each other, effectively dividing the detector into 1600 independent pixels. Using spatial and time correlations, the implants were linked with their subsequent α or proton decays and with decays of their daughter and granddaughter nuclei. The DSSD strips were gain-matched using a ^{244}Cm-^{240}Pu α source and the sum of all strips was also calibrated using known α activities produced in the ^{78}Kr+^{96}Ru reaction, namely, ^{167}Os, ^{168}Os, ^{171}Ir, ^{172}Pt, ^{171}Pt, ^{171}Au, and ^{172}Au. The energies of these α lines were adopted from Ref. [7] and references therein, except for ^{171}Au where the data were taken from Ref. [8]. In order to measure lifetimes every event was time stamped and half-lives were fitted to the distribution of times between correlated implant and decay events using the maximum likelihood method [9].

Figure 1(a) presents the energy spectrum of all decays detected in the DSSD using the ^{78}Kr+^{96}Ru reaction at an energy of 375 MeV. In Fig. 1(b) only decays correlated within 40 ms with implanted mass 172 residues are shown. The spectrum is dominated by strong lines corresponding to the α decay of ^{172}Au and ^{172}Pt (corresponding to $1p1n$ and $2p$ channels, respectively). In addition, an isolated group consisting of three events is visible above 7 MeV in Fig. 1(b). These three events are also present in Fig. 1(c) which contains decays followed within 100 ms by α particles corresponding to the decay of ^{168}Pt [10] ($E_\alpha \approx 6.83$ MeV), and thus are assigned to the decay of the previously unknown isotope ^{172}Hg. Based on these three events an energy of 7350(12) keV and a half-life of $250(^{+350}_{-90})$ μs were deduced for the α decay of ^{172}Hg.

The decay spectrum measured for the ^{80}Kr+^{96}Ru reaction at 400 MeV is shown in Fig. 2(a). The significant background visible at higher energies in Figure 2(a) is associated with implant events for which the focal plane detector did not register a heavy residue, leading to the misinterpretation of this event as a decay. Fig. 2(b) presents decays which took place within 40 ms after the implantation of mass 173 residues. The spectrum is dominated by two α lines corresponding to ^{173}Au and ^{173}Pt (corresponding to $p2n$ and $2pn$ channels, respectively). A group of α particles with energies in excess of 7 MeV can be seen as well in Fig. 2(b). Seven of these events were found to be followed within 100 ms by α particles with energies of about 6.7 MeV, corresponding to the known α decay of ^{169}Pt [11,7] [see Fig. 2(c)]. This leads to an unambiguous assignment of this group to the decay of a new isotope ^{173}Hg. Based on the properties of these seven events, an energy of 7211(11) keV and half-life of $0.93(^{+0.57}_{-0.26})$ ms were extracted for the α decay of ^{173}Hg.

The results of the ^{80}Kr+^{96}Ru experiment at 375 MeV are shown in Fig. 3. The topmost panel shows the total decay spectrum whereas Fig. 3(b) contains only decays following mass 174 implants within 40 ms. The decays which were followed within 100 ms by 6.55-MeV α particles, corresponding to the decay of ^{170}Pt [7], are shown in the bottom panel. The line at ≈ 7 MeV visible in all three spectra corresponds to the α decay of ^{174}Hg. From the present data a decay energy of 7066(8) keV and half-life of $1.9(^{+0.4}_{-0.3})$ ms were deduced, based on the 31 observed events. These results agree well with the previous measurement of 7069(11) keV and $2.1(^{+1.8}_{-0.7})$ ms reported in Ref. [2]. However, the statistical errors are smaller since only four events assigned to ^{174}Hg were observed in Ref. [2].

It should be noted that the number of observed daughter Pt α particles correlated with the decay of ^{172}Hg, ^{173}Hg, and ^{174}Hg, respectively, is consistent with a 100% α-decay branch in ^{168}Pt, ^{169}Pt, and ^{170}Pt. Table I summarizes the experimental results obtained for light Hg isotopes, including the estimated cross sections for ^{172,173,174}Hg. The FMA efficiency necessary to estimate cross sections was not

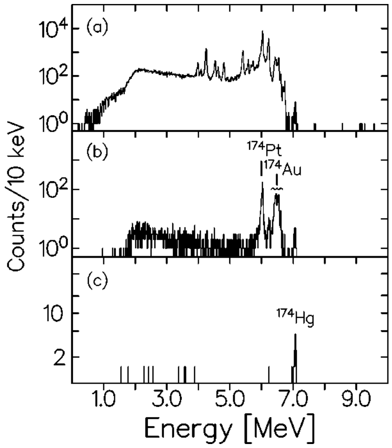

FIG. 3. Energy spectra of α particles measured in the DSSD using the ^{96}Ru+^{80}Kr reaction at 375 MeV: (a) all decays; (b) decays following mass 174 residues within 40 ms; (c) decays followed by 6.55 MeV ^{170}Pt α particles within 100 ms.

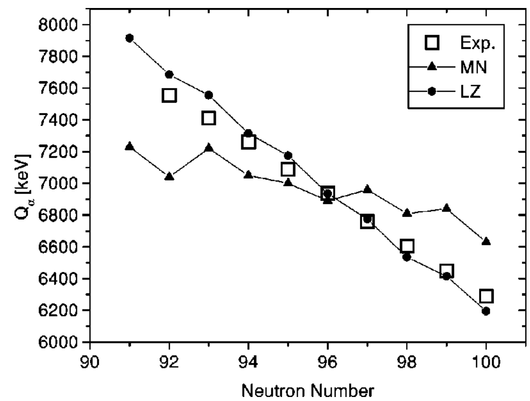

FIG. 4. α-decay Q values of neutron-deficient isotopes of Hg. The open squares represent data, including the α-decay Q values for ^{172,173,174}Hg deduced in this work. The filled circles and triangles represent α-decay Q values calculated using mass tables by Liran and Zeldes and by Möller and Nix, respectively.

measured, but an assumed value of 10% should give cross sections accurate to within a factor of 2. The nuclei ^{172}Hg and ^{173}Hg were produced with cross sections of 9 nb and 15 nb, respectively. The cross section for populating ^{174}Hg is 330 nb, i.e., one order of magnitude higher than for ^{172}Hg and ^{173}Hg. It is also about one order of magnitude higher than the cross section reported in Ref. [2], where ^{174}Hg was produced as a 6n evaporation channel.

The α-decay half-lives can be calculated using the Rasmussen method [12]. In this method, the decay constant λ is factorized into the reduced width δ^2 and the barrier penetration factor P according to the formula: $\lambda = \delta^2 \cdot P/h$, where h is Planck's constant. The barrier penetration factor is calculated using the WKB approximation to extract δ^2. Alternatively, ^{212}Po reduced width can be used to calculate the half-life ($t_{1/2}^{\mathrm{Rasm}}$). Calculated half-lives and reduced α-decay widths for the light Hg isotopes are shown in Table I. The partial β decay half-lives predicted for ^{172,173,174}Hg are 0.2 s, 0.24 s, and 0.35 s, respectively [13]. Since these values are at least two orders of magnitude longer than the measured half-lives, β-decay branches were neglected. The reduced α-decay widths deduced for ^{172,173,174}Hg are very close to the reference value of 70 keV obtained for ^{212}Po and other even-A Hg isotopes. This indicates that these α decays can be associated with $\Delta l = 0$ unhindered transitions.

Figure 4 compares the Q values for the light Hg isotopes in the mass range 172–180, including the values obtained for ^{172,173,174}Hg in the present work, with those calculated using mass tables by Liran and Zeldes [14], obtained using a semiempirical shell-model mass formula, and by Möller and Nix [15], obtained using macroscopic-microscopic calculations. As can be seen from Fig. 4, the Liran and Zeldes Q_α values fit the experimental data rather well, even though they overpredict somewhat the Q_α values for the lightest Hg isotopes ($N=92,93$). In contrast, the calculations by Möller and Nix overpredict the Q_α value of ^{180}Hg by about 400 keV, approach the experimental values at $N=96$, and significantly underpredict the Q_α values for the lightest known Hg isotopes (by about 600 keV for ^{172}Hg).

In Ref. [8], a mass excess of $-16300(33)$ keV was deduced for ^{170}Pt, by following the decay chain down to ^{150}Ho, a nucleus with a measured mass [16]. Based on the assumption that the observed α decay of ^{174}Hg connects to the ground state of ^{170}Pt, the mass excess of ^{174}Hg is $-6607(34)$ keV. In the recent mass evaluation of Audi and Wapstra [17] mass excesses of $-11150(360)$ and $-12650(310)$ keV were estimated for ^{168}Pt and ^{169}Pt, respectively. These values combined with the α-decay Q values deduced in the present work give estimated mass excesses of $-1170(360)$ keV and $-2810(310)$ keV for ^{172}Hg and ^{173}Hg, respectively.

Finally, the cross sections for producing these Hg isotopes are quite small. While the predictions by Nazarewicz of a new superdeformed region in the light Hg isotopes are intriguing, the population cross sections are too low for $^{172-174}$Hg to allow for a proper search for superdeformation in these nuclei using even the most powerful existing γ-ray arrays such as Gammasphere. However, low spin states in ^{174}Hg are within reach.

In summary, the α decays of two new isotopes ^{172}Hg and ^{173}Hg were observed for the first time, and the α decay of ^{174}Hg was studied with improved accuracy. The reduced α-decay widths indicate a $\Delta l = 0$ character for the observed transitions. The α-decay Q values deduced for ^{172,173,174}Hg are reproduced very well using the mass tables of Liran and Zeldes, whereas values calculated using mass tables by Möller and Nix deviate from the data with decreasing neutron number.

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