Evidence for a high-spin β-decaying isomer in ^{177}Lu

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Nuclei in the $A\sim180$ region have been populated and investigated in a series of multinucleon transfer and deep-inelastic reactions involving an 11.4 MeV per nucleon ^{136}Xe beam produced by the GSI UNILAC accelerator, impinging on a selection of tantalum and tungsten targets. The reaction products were released from a thermal ion source and subsequently mass selected using the GSI on-line mass separator. The unexpectedly high yield of γ rays associated with the decay of the well established $K^{\pi}=37/2^{-}, t_{1/2}=51.4$ min isomer in $^{177}_{72}$Hf and anomalous half-life characteristics associated with this decay lead to these data being interpreted as the β^{-} decay of a high-K isomer in the mother nucleus, ^{177}Lu. By comparing the experimental findings with the predictions obtained from multi-quasiparticle blocked-BCS-Nilsson calculations, the proposed decay is suggested to be from a $K^{\pi}=39/2^{-}$ five-quasiparticle state in $^{177}_{71}$Lu. A half-life of 7 ± 2 min is determined for this β-decay path which is estimated to have an excitation energy of ≈3.9 MeV above the ^{177}Lu ground state.

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I. INTRODUCTION

The region of near-stable nuclei with $A\sim180$ has a number of specific areas of structural interest, including the presence of axially deformed, high spin, metastable states. This region is well known to be energetically favorable for high-Ω orbitals[1] which when coupled together can give rise to particularly long-lived states of high K [1]. If these states compete energetically with the collective rotational states, they can result in isomeric states with lifetimes ranging from nanoseconds up to years (e.g., Refs. [2–7]).

A number of theoretical works have indicated (e.g., Ref. [8]) that there are good prospects for finding new, high-spin isomers in neutron-rich isotopes which cannot be accessed by fusion-evaporation reactions induced by stable-isotope beams. More recent calculations [1,9,10] support this view with quantitative predictions, and there has recently been considerable experimental success in probing this region using deep-inelastic [2,11–15] and relativistic projectile fragmentation reactions [16–22]. However, in only one of these examples has a new K isomer with half-life greater than 1 s been established, specifically the $K^{\pi}=8^{-}, t_{1/2}=48$ s isomer in ^{184}Hf, discovered using the GSI on-line mass separator [11]. [Note that for long-lived isomeric decays ($\tau>10$ ms), the correlation between the ion of interest and the γ rays decaying from the isomer is lost in the projectile-fragmentation method due to the predominance of random background events.]

This work describes the results of two experiments performed to investigate decays in the temporal regime ranging from seconds to hours for stable and neutron rich $A\sim180$ nuclei using deep-inelastic collisions. The results presented in the current work focus specifically on the $A=177$ isobaric chain with particular interest on the production and decay of $^{177}_{71}$Lu. The nuclei studied were produced following collisions between a ^{136}Xe beam provided by the GSI UNILAC accelerator impinging on natural tantalum and enriched ^{186}W targets placed in a thermal ion source [23]. The residual ions of interest were extracted from the ion source and mass analyzed using the GSI on-line mass separator. This work can be

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[1]Ω is the single-particle angular momentum projection on the nuclear axis of symmetry and $K=\Sigma_i\Omega_i$ is the projection of total angular momentum on the same axis.

thought of as extension of earlier studies which highlighted the effectiveness of using multinucleon transfer reactions to populate neutron-rich nuclei in this region [11,23–26]. Initial reports of this work have been published in Refs. [27,28].

II. EXPERIMENTAL DETAILS

Beams of 10-50 particle-nA of ^{136}Xe at a laboratory energy of 11.4 MeV per nucleon were supplied by the GSI UNILAC and incident on (i) 40 mg/cm^2 thick enriched ^{186}W and (ii) 30 mg/cm^2 thick natural tantalum targets, placed inside thermal ion sources [29,30]. The positively charged reaction products resulting from multinucleon transfer and deep-inelastic processes were extracted via a negative polarity extraction voltage of 50 kV and subsequently selected by isobars using the GSI mass separator [31,32]. The mass-selected beam was taken to the measuring system which involved a tape system mounted at one of the beam lines of the mass separator. By utilizing a variety of different tape-cycle periods, the removal of unwanted, longer-lived decays was achieved.

In the first experiment (which will henceforth be referred to as the "Cluster" experiment), the radiation detection system incorporated a γ-ray array which consisted of a seven-element cluster germanium (Ge) detector [33–35] together with two standard, coaxial hyperpure germanium detectors of 60–70 % efficiency relative to a standard NaI(Tl) detector. In addition a planar germanium spectrometer was incorporated to increase the detection sensitivity for low-energy γ and x rays. A plastic scintillator was also used to detect the emitted β^+, β^-, and/or atomic electrons following internal conversion decays. The tape station allowed the removal of the mass-separated source from the $\beta-\gamma$ detection array at the end of the "grow-in cycle."

In the second experiment [referred to as the Total Absorption Spectrometer (TAS) experiment], the measuring system was composed of two stations. First, a monitor station was used which consisted of a large-volume, germanium (Ge) γ-ray detector, operated in coincidence with a plastic scintillator for electron detection. The second device, a TAS station, consisted of a large-volume NaI(Tl) TAS [36,37]. A small-volume Ge detector and a 1 mm thick silicon (Si) detector, each covering a little under 2π steradian of detection geometry as viewed from the source, were both housed inside the TAS detector. The Ge detector enabled high resolution measurement of x rays and low-energy γ rays, while the silicon detector was used for the measurement of β particles and conversion electrons. Further details of the TAS can be found in Ref. [36]. The mass-selected beam was implanted in the plastic tape, with the resulting radioactive source being transported periodically to the radiation detectors.

III. EXPERIMENTAL RESULTS

Various targets were bombarded with the ^{136}Xe beams. For specific experiments, a summary of investigated mass numbers, transport tape cycle, and the total run times are listed in Table I.

TABLE I. Summary of experimental parameters concerning, mass, tape-cycle period, and target selections investigated in the two experiments of the current work.

Experiment	Mass	Target	Time cycle (s)	Run time (min)
Cluster	177	^{nat}Ta	8	30
	177	^{nat}Ta	160	599
	177	^{186}W	800	107
	177	^{nat}Ta	1600	321
	177	^{186}W	1600	131
	177	^{nat}Ta	8000	10
	177	^{nat}Ta	9600	136
	177	^{nat}Ta	16000	215
	178	^{nat}Ta	8	217
	178	^{nat}Ta	800	358
	182	^{186}W	160	148
	182	^{186}W	3200	55
TAS	177	^{186}W	16	316
	177	^{nat}Ta	80	248
	177	^{186}W	80	198
	177	^{nat}Ta	320	540
	177	^{186}W	320	343
	177	^{186}W	640	200
	177	^{nat}Ta	1200	975
	177	^{nat}Ta	2700	190
	177	^{nat}Ta	3600	60

A. Cluster experiment

Figure 1 shows the grow-in γ-ray spectra for $A=177$ using a tantalum target at three different tape-cycle periods. The shortest tape cycle (160 s) clearly identifies the short-lived 105 keV and 518 keV transitions following the ground-state β decay ^{177}Tm$\rightarrow$^{177}Yb [24]. The 1600 and 16 000 s tape-cycle spectra shown in Fig. 1 highlight the γ-ray lines at 122, 150, and 1080 keV which correspond to transitions following the β decay from the longer-lived ground-state decay of ^{177}Yb to ^{177}Lu [38].

The results obtained from the two longer cycle periods of 1600 and 16 000 s, shown in Fig. 1, demonstrate a significantly increased number of lines, specifically those coming from the previously identified $K^{\pi}=37/2^-$ isomer in ^{177}Hf [6] which has a well established half-life of 51.4±0.5 min [39]. Figure 2 shows the grow-in curves for the time dependent γ-ray intensity of the lines associated with this ^{177}Hf isomer (i.e., sum of the 214, 277, 295, 312, and 327 keV lines). We note that the value of 76 min from the best, single-component fit to these data is considerably longer than the established half-life value of 51.4±0.5 min [39].

Applying the $\chi^2_{min}+1$ method [40] for estimating the un-

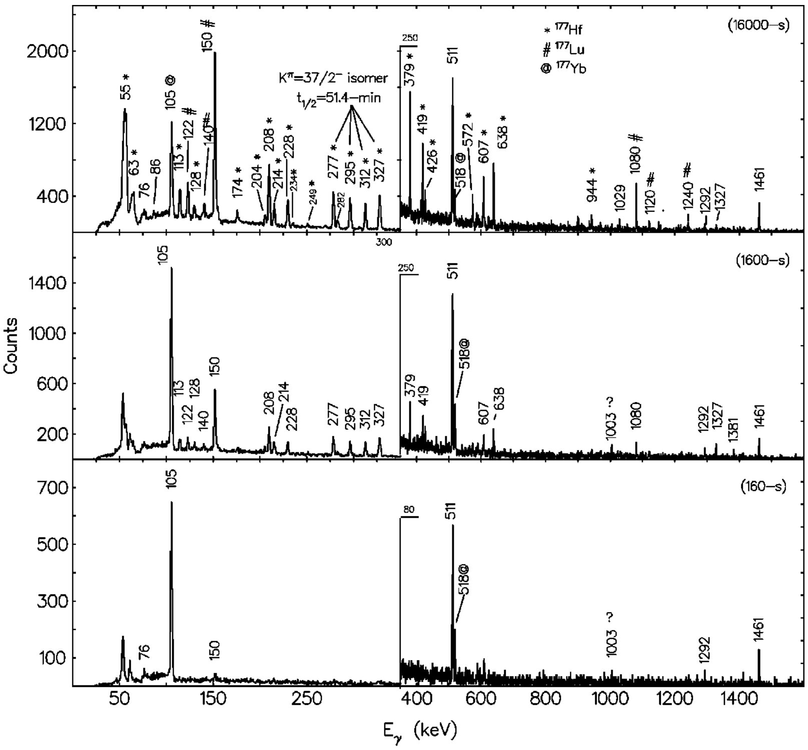

FIG. 1. Cluster array γ-ray spectra for A = 177 using the tantalum target. Note the effect of tape-cycle selection on the measurement of activities with differing half-lives. The total collection times were 599, 321, and 215 min for the 160, 1600, and 16 000 s cycles, respectively. The labels indicate the nuclei which the γ-ray transitions decay in.

certainty of the minimum value yields an apparent half-life of 76^{+16}_{-9} min (see inset of Fig. 2).[2]

One possible explanation for the disparity between the measured and published lifetime is that the $K^\pi = \frac{37}{2}^-$ decay in ^{177}Hf, as observed in this experiment, is actually fed by a higher-lying, β-decaying isomeric state in ^{177}Lu. The evidence put forward to support this suggestion is outlined below.

(i) The clear observation of lines from the $K^\pi = \frac{37}{2}^-$ isomer in ^{177}Hf is at odds with the fact that the release of refractory elements such as hafnium is expected to be suppressed from a thermal ion source.

(ii) The measured single-component (apparent) half-life for the ^{177}Hf $K^\pi = 37/2^-$ isomer of 76^{+16}_{-9} min is inconsistent at the $>2\sigma$ level with the previous measurements for this decay of $t_{1/2} = 51.4 \pm 0.5$ min.

In order to investigate the suggestion that direct release of hafnium isotopes is highly suppressed, two other settings were analyzed in detail, namely those involving the mass-separated A = 178 and 182 secondary beams. These were chosen in order to search for the direct population (or otherwise) of isomeric ($K^\pi = 8^-$) states in hafnium nuclei.

The specific decays of interest were the long-lived $K^\pi = 8^-$ isomeric states in ^{178}Hf [4] and ^{182}Hf [6,23,41] which have intrinsic half-lives of 4 s and 61.5 min, respectively. Note that while the $K^\pi = 8^-$ isomeric state in ^{178}Hf can be fed from the β decay of the $K^\pi = 9^-$ low-lying state in the ^{178}Lu mother nucleus [42], this scenario does not seem to be valid for the ^{182}Hf isomer (see Fig. 3.)

Figure 4 displays the γ-ray spectrum for mass 178, using the tantalum target in a thermal ion source with an 800 s tape cycle. This spectrum clearly shows the lines deexciting the $K^\pi = 8^-$ isomer in ^{178}Hf which are characterized by γ-ray energies of 89, 93, 213, 326, and 426 keV. The half-life de-

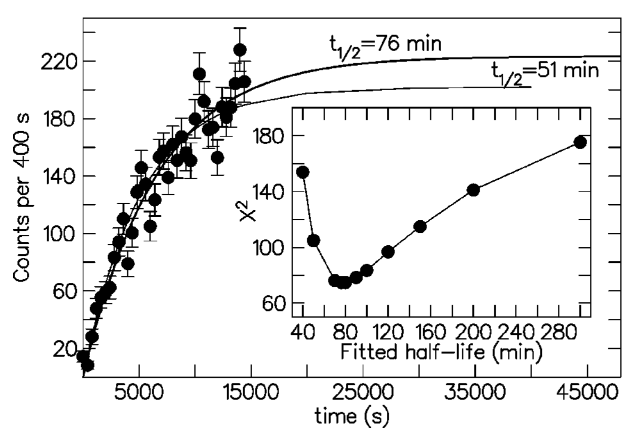

FIG. 2. Single-lifetime grow-in fit for γ rays assigned to the $K^\pi = 37/2^-$ isomer in ^{177}Hf (214, 277, 295, 312, and 327 keV) from the Cluster experiment. The inset shows the χ^2 values for single decay component grow-in fit of the decays from $K^\pi = 37/2^-$ isomer in ^{177}Hf, with the asymptotic value allowed to vary to the minimum value for each half-life value. A best fit for a fixed half-life of 51.4 min is also shown for comparison. This analysis gives a minimum value for the single-component decay for these data of $t_{1/2} = 76^{+16}_{-9}$ min.

[2]A constant ^{136}Xe primary beam intensity and constant TIS performance over the entire measuring period are required for the application of this fitting procedure to be valid. The current data were only taken for a single 16 000 s cycle. A variation in primary beam intensity might be averaged out if many cycles had been taken. However we also note that the count rate of the short-lived ^{177}Tm activity (105 keV transition) remained steady throughout for the current data.

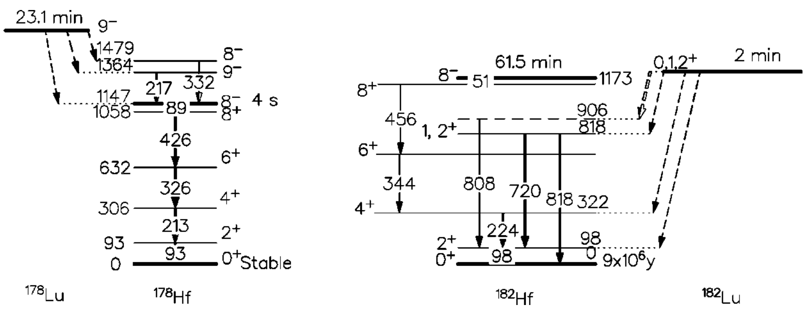

FIG. 3. Schematic decay schemes for the β-fed states in ^{178}Hf and ^{182}Hf. For reference, the nonobserved decay from the $K^{\pi}=8^{-}$ isomer in ^{182}Hf is also shown. The data are taken from Refs. [4,6].

duced for the sum of the grow-in curves of these five transitions yields a value of $t_{1/2}=23(1)$ min, assuming a single-component decay constant. This result, shown in Fig. 5, is consistent with the feeding of the ^{178}Hf isomer by the ^{178}Lu β decay with $T_{1/2}\approx 23.1$ min [42].

Figure 6 displays the γ-ray spectrum obtained for $A=182$, where the lines fed by the (low spin) β^{-} decay of ^{182}Lu are observed, but no obvious direct population of the $K=8^{-}$ isomer is present. (Note the absence of the transitions at 344 and 456 keV corresponding to the yrast $6^{+}\rightarrow 4^{+}$ and $8^{+}\rightarrow 6^{+}$ transitions in ^{182}Hf, respectively [6,41].) The half-life deduced from the grow-in curve gives a value of 2.30 ± 0.25 min as shown in Fig. 7, consistent with the published value for the half-life of the ground state β^{-} decay of ^{182}Lu of $t_{1/2}=2.0\pm 0.2$ min [23]. As Fig. 6 also demonstrates, there is *no* evidence for the population of the $K^{\pi}=8^{-}$ isomer ($t_{1/2}=61.5$ min) in ^{182}Hf [6,41], via a low-lying, high spin β^{-}-decaying state in ^{182}Lu. The obvious lack of direct population of the ^{182}Hf $K^{\pi}=8^{-}$ isomer is consistent with the conclusion that the release of hafnium ions from the thermal ion source used in the current experiment was highly suppressed, strengthening the argument that the ^{177}Hf $K^{\pi}=37/2^{-}$ isomer is actually fed by a β-decaying state in ^{177}Lu.

Two methods of analysis were undertaken to determine the lifetime of the β^{-}-decaying ^{177}Lu^{m2} state itself and to identify any internal decay branches from the proposed $K^{\pi}=39/2^{-}$ state in ^{177}Lu to lower-lying states in this nucleus via γ decay. (The spin/parity assignment for the proposed state in ^{177}Lu will be discussed in the following section.)

The first method made use of a two-component fit to the grow-in curve for the observed γ-ray intensities from the $K^{\pi}=37/2^{-}$ isomer in ^{177}Hf, fixing the half-life of the lower ($K^{\pi}=37/2^{-}$ isomeric) state to the published value of $t_{1/2}=51.4$ min.

The expression for the grow-in rate R for a two-component grow-in is given by

$$R=A\times[r(1-e^{-\lambda_1 t})-(r-1)(1-e^{-\lambda_2 t})], \qquad (3.1)$$

where A is a constant, $r=\lambda_2/(\lambda_2-\lambda_1)$, λ_1 is the decay constant of the higher-lying state, and λ_2 is the decay constant of the lower-lying state.

Using this expression, the grow-in of the data shown in Fig. 2 were fitted to the two-component expression given above. The result is shown in Fig. 8. By fixing the value of λ_2 to a value corresponding to a half-life of the lower state (^{177}Hf $K^{\pi}=37/2^{-}$) of 51.4 min, a value of $t_{1/2}=6$ min can be extracted for the higher-lying decay component. A χ^2 minimization for the lifetime of the upper level using this two-component technique is shown in Fig. 9, yielding a best fit value of 6^{+3}_{-2} min for the proposed state.

The application of the two-component-decay formula is based on the premise of a constant lutetium production and prompt release from the ion source. In previous work, the release properties of lutetium from a thermal ion source have been measured [43] and affected the decay constants in expression (3.1). Due to the uncertainties in the original premise for this analysis due to the release properties of the ion source, a second, independent method to determine the half-life of the proposed higher-lying decay was used. This second method was used to search for internal decays in

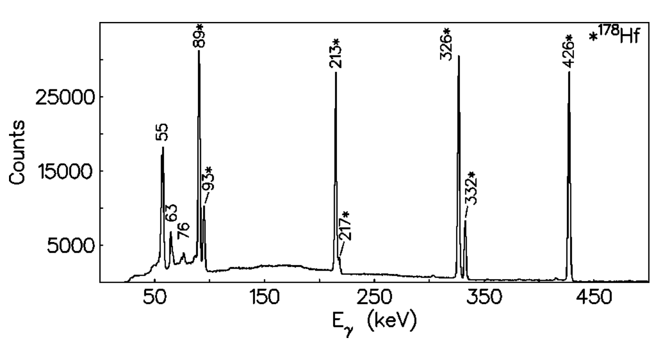

FIG. 4. γ-ray spectrum for the $A=178$ setting with a tape cycle of 800 s for the tantalum target from the Cluster experiment. Note the clear identification of lines following the decay from the $t_{1/2}=4$ s,$K^{\pi}=8^{-}$ isomer in ^{178}Hf [42], which is populated by the β decay of the $K^{\pi}=9^{-}$ state in ^{178}Lu.

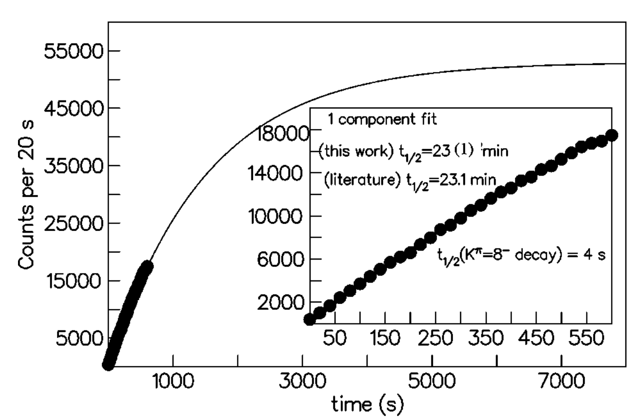

FIG. 5. Grow-in curve for the transitions occurring in the decay of the $K^{\pi}=8^{-}$ isomer in ^{178}Hf, showing a half-life of 23.3 min, consistent with a population via the β^{-} decay of the low-lying high spin state in ^{178}Lu ($t_{1/2}=23.1$ min).

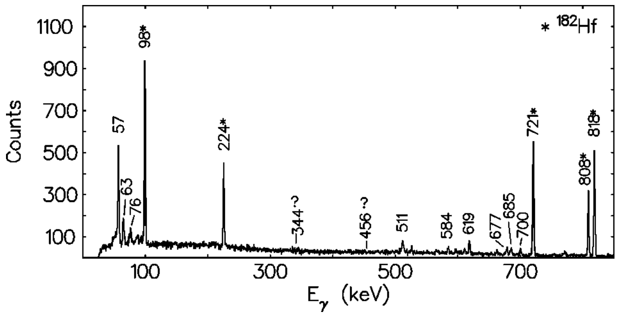

FIG. 6. γ-ray spectrum observed for the $A=182$ setting with a tape-cycle period of 3200 s. Note the observation of the $4^+\rightarrow2^+$ (224 keV) and $2^+\rightarrow0^+$ (98 keV) transitions in ^{182}Hf (from ^{182}Lu β decay, see Fig. 3), but the absence of the $6^+\rightarrow4^+$ (344 keV) and $8^+\rightarrow6^+$ (456 keV) transitions below the ^{182}Hf $K^\pi=8^-$ isomer [6,41].

^{177}Lu and β-delayed transitions associated with the possible ^{177}Lu isomer by investigating the ratio of counts for individual γ-ray transitions in the 1600 s and 16 000 s tape-cycle spectra for $A=177$. In particular, we have evaluated the intensity ratio for the β-delayed γ rays of $^{177}_{70}$Yb ($t_{1/2}$ $=1.911$ h) by comparing the spectra accumulated during the 1600 and 16 000 s tape cycles. As can be seen from Table II and Fig. 10, this procedure gives intensity ratios of between 2 and 3.

The observed transitions following the depopulation of the $K^\pi=37/2^-$ isomer in $^{177}_{72}$Hf are also found to have a weighted-average ratio of ≈3. We note the shorter half-life of 85 s for the transitions associated with the $^{177}_{69}$Tm $\rightarrow^{177}_{70}$Yb decay which have a much lower weighted mean of 0.83 for this intensity ratio.

In Fig. 11, four previously unreported transitions with energies of 413, 1003, 1292, and 1327 keV (labeled with ?) were identified with ratios corresponding to decay half-lives in the few minutes regime, consistent with the estimated half-life of 6^{+3}_{-2} min min for the decay of the proposed K^π $=39/2^-$ state in ^{177}Lu. Since the decay of such a state to the $K^\pi=37/2^-$ state in ^{177}Hf could proceed by a direct allowed Gamow-Teller ($\Delta I=1,\Delta\pi=0$) β decay, one would expect on the basis of phase space arguments that most of the decay goes directly to the $K^\pi=37/2^-$ isomer. A comparison of the yield ratio between the ^{186}W and tantalum targets for the four unknown transitions is carried out in Fig. 12. The 1003 keV has a lower yield compared to the 518 keV transition from the $t_{1/2}=85$ s, ^{177}Tm ground-state decay, while the ratios of the other three unplaced transitions agree within the 1σ uncertainty limit with that of the 518 keV line, suggesting that the 1003 keV transition comes from a decay other than the ^{177}Tm.

A proposed partial decay scheme for ^{177}Lu and ^{177}Hf nuclei incorporating an assumed $K^\pi=39/2^-$ isomer in ^{177}Lu (see the following section for assignment of spin and parity) is shown in Fig. 13. All known transitions from the K^π $=23/2^-$ isomer in ^{177}Lu and the $K^\pi=37/2^-$, 51 min isomer in ^{177}Hf are also shown for completeness.

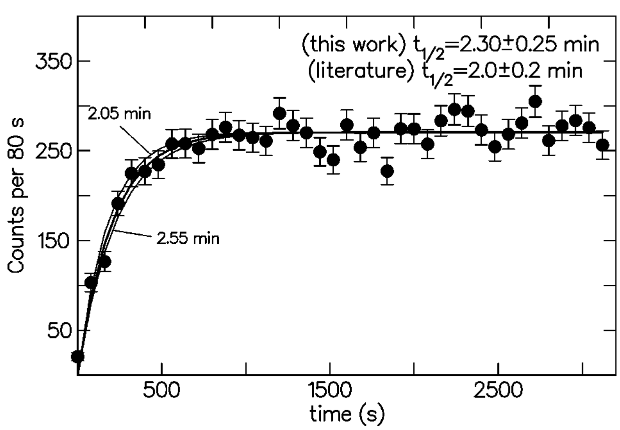

FIG. 7. Grow-in curve for the intensities of the transitions at 98, 224, 721, 808, and 818 keV following the β^- decay of ^{182}Lu to ^{182}Hf from the Cluster experiment. The tape cycle was 3200 s.

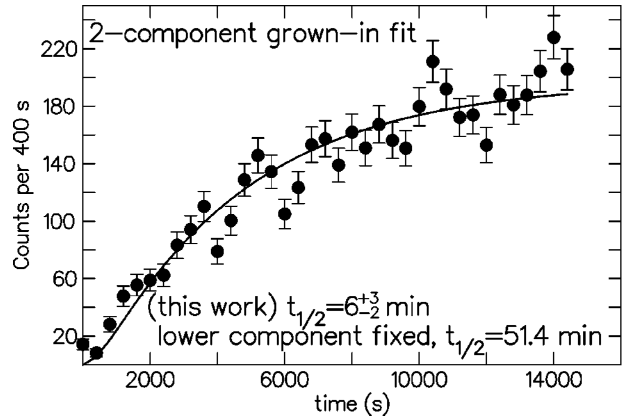

FIG. 8. Two-component grow-in fit for transitions depopulating the $K^\pi=37/2^-$ isomer in ^{177}Hf (fixing the half-life of the K^π $=37/2^-$ isomer in ^{177}Hf to be 51.4 min [6,39]).

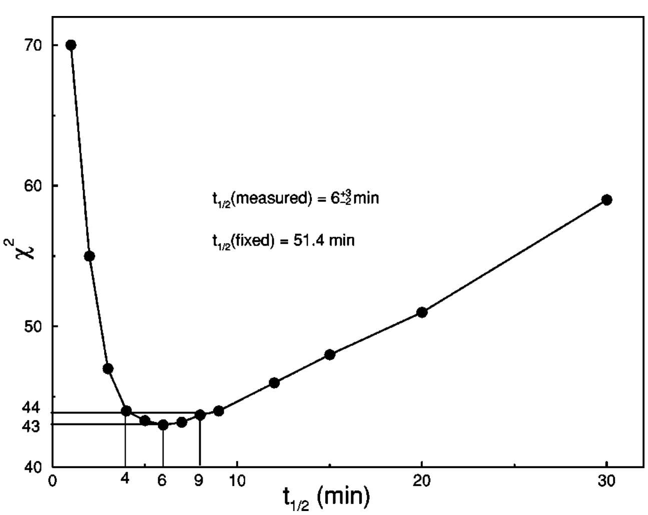

FIG. 9. Plot of χ^2 values for the proposed $K^\pi=39/2^-$ β-decaying state in ^{177}Lu. The variable $t_{1/2}$ value refers to the higher lying isomer, after performing a two-component decay fit for the observed transitions decaying from the (fixed) $t_{1/2}=51.4$ min isomer in ^{177}Hf.

TABLE II. Intensity ratio as determined for $A=177$ γ-ray transitions with 16 000 and 1600 s tape cycles, using a Ta target in a thermal ion source. The previously unidentified lines are indicated with a question mark and have apparent decay half-lives in the few minutes regime. The element symbol in the *Assignment* column represents the respective $A=177$ isotope, except for the background lines marked by e^+e^- and ^{40}K. The 1461 keV background line from ^{40}K was used as a normalization (see also Fig. 10).

E_γ	N_{16000}	N_{1600}	$R_{(16000/1600)}$	Mother assignment
104.5	4400±150	5425±220	0.81±0.04	Tm
113.5	1170±90	330±70	3.5±0.8	Hf
122.1	1320±120	310±60	4.3±0.9	Yb
128.9	570±70	200±20	2.85±0.45	Hf
139.3	680±50	150±30	4.53±0.96	Yb
150.9	6800±300	1960±90	3.46±0.22	Yb
174.9	470±90	90±35	5.23±2.13	Hf
204.6	440±60	135±15	3.26±0.57	Hf
208.6	2510±130	640±30	3.92±0.27	Hf
214.2	820±300	380±40	2.16±0.24	Hf
228.6	1060±50	395±15	2.68±0.16	Hf
234.4	190±20	55±10	3.45±0.72	Hf
249.9	185±15	75±15	2.46±0.53	Hf
277.5	1335±35	520±10	2.57±0.08	Hf
282.0	285±15	110±30	2.59±0.72	Hf
295.1	1315±100	520±60	2.53±0.35	Hf
305.7	120±15	70±10	1.71±0.32	Hf
311.5	1035±60	410±25	2.52±0.21	Hf
326.8	1640±55	660±20	2.48±0.11	Hf
378.5	615±40	285±25	2.16±0.23	Hf
413.9	110±35	55±10	2.00±0.73	?
418.5	420±30	200±30	2.10±0.35	Hf
426.4	120±10	140±25	0.86±0.16	Hf
510.7	985±30	1290±80	0.76±0.05	e^+e^-
517.9	100±10	230±40	0.43±0.09	Tm
572.5	170±10	90±10	1.89±0.24	Hf
588.3	60±25	80±25	0.75±0.39	Tm
606.5	320±55	165±20	1.94±0.41	Hf
622.4	50±30	60±10	0.83±0.52	Tm
637.6	325±25	100±20	3.25±0.69	Hf
898.7	65±15	30±10	2.16±0.87	Yb
941.4	88±15	25±10	3.52±1.53	Yb
1003.1	40±5	50±15	0.80±0.26	?
1027.8	60±10	25±5	2.40±0.62	Yb
1080.0	290±30	100±15	2.90±0.52	Yb
1119.6	60±15	38±10	1.58±0.57	Yb
1149.6	45±10	10±6	4.5±0.63	Yb
1241.0	60±20	40±5	1.5±0.53	Yb
1291.7	40±10	55±15	0.73±0.27	?
1327.3	37±8	83±15	0.45±0.12	?
1460.6	180±15	130±5	1.38±0.12	^{40}K

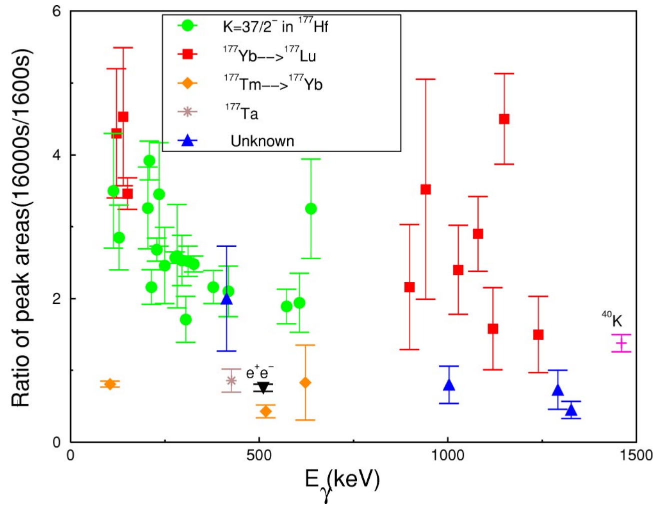

FIG. 10. (Color online) Ratio of γ-ray intensities measured for the 16 000 s and 1600 s cycles for mass 177 using the tantalum target. The data points for the background e^+e^- and ^{40}K lines are also plotted as reference points.

B. TAS experiment

The TAS technique was used in the second experiment to search for more evidence supporting the existence of the proposed ^{177}Lu^{m2} high spin K isomer. The effect of putting different gates on the TAS energy spectrum and projecting the coincident Ge γ-ray spectrum is demonstrated in Fig. 14, which shows TAS coincidences (total projection) in the upper panel. The strongest previously unidentified (now marked as hafnium) transition, at 89 keV, is prominent. It is

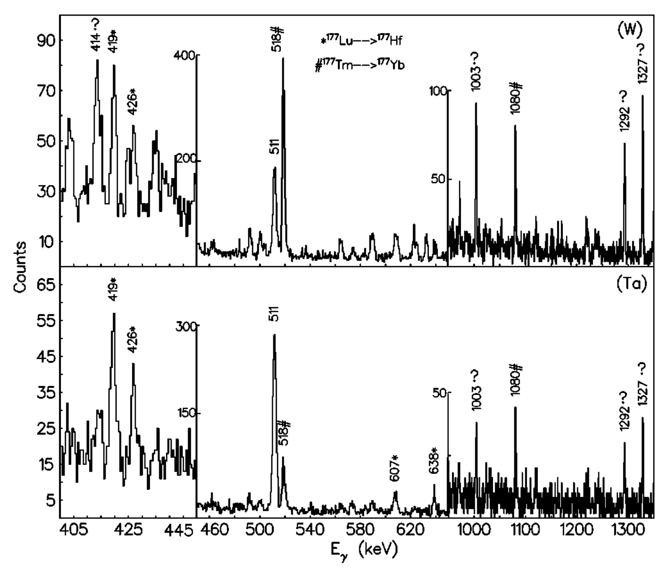

FIG. 11. Comparison of the γ-ray spectra obtained for $A=177$ using a 1600 s tape-cycle period for mass 177 with targets of ^{186}W and tantalum, respectively. Note the presence of the 1003 keV line which is a candidate for a transition from a state above the $K^\pi=37/2^-$ isomer in ^{177}Hf, fed directly by the β^- decay of the proposed $K^\pi=39/2^-$ state in ^{177}Lu. The total collection time was 131 min for the ^{186}W and 321 min for the tantalum target, respectively.

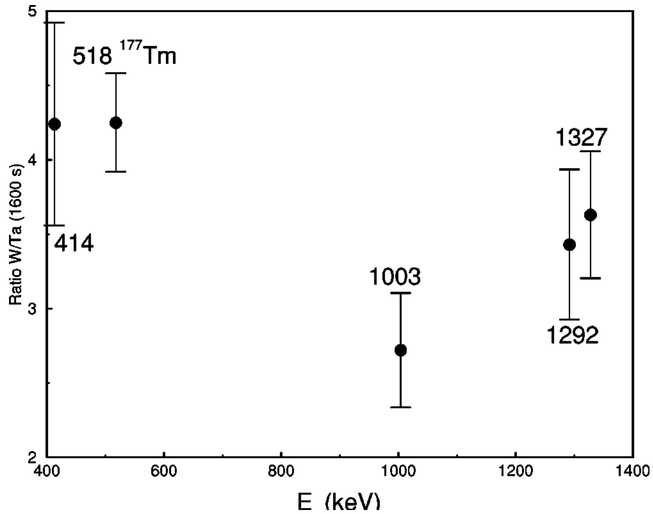

FIG. 12. Ratio between the γ-ray intensities as measured by using ^{186}W and tantalum targets with a 1600 s tape cycle for $A = 177$.

also (weakly) observed in the Si-detector coincidence (middle panel) but is effectively absent in TAS anticoincidence (lower panel.)

Examining the TAS events in coincidence with the 89 keV transition as measured in the Ge detector (lower panel of Fig. 15) shows a prominent peak at $E_\gamma = 1003$ keV. The small cluster of counts to the low-energy side of this peak may have a connection with a more complex cascade. The central panel of Fig. 15 represents the 208 keV ^{177}Lu $\rightarrow$ ^{177}Hf transition [44,45] measured by the TAS coincidence with 113 keV γ rays recorded in the small Ge detector, while the upper panel shows the 1080 keV transition in the decay of ^{177}Yb $\rightarrow$ ^{177}Lu [38] observed in the TAS when gated by the 150 keV events from the Ge detector. These two examples illustrate how individual γ-ray peaks appear in the TAS spectra. The energy of the peak as determined from the TAS spectrum in the lower panel of Fig. 15 (in coincidence with the 89 keV γ-ray line) is 999 ± 4 keV.

Note that the 1003 keV peak was also observed in the Cluster experiment (see Fig. 1) and was identified there as a transition of potential interest with regard to the hypothetical ^{177}Lu high-K isomer decay. Gating on the 1003 keV transition in the TAS, the 89 keV transition is clearly present in the coincident Ge spectrum. Figure 16 illustrates that the 89 keV transition is associated with hafnium K_α x rays. Furthermore, the x-ray intensity, relative to the 89 keV γ-ray intensity, implies a small electron-conversion coefficient, and hence $E1$ character for the 89 keV transition. The experimental α_K value of 0.42 ± 0.15 derived from x-ray to γ-ray intensity ratio for the 89 keV transition is consistent with the theoretical value of $\alpha_K(E1) = 0.40$ [46].

We conclude that the 89 and 1003 keV transitions are in coincidence, and that they are associated with internal decays in ^{177}Hf. A single-component exponential fit was applied to the time characteristic of the intensity of the 89 keV events recorded by the small Ge detector in coincidence with the TAS. The result is shown in Fig. 17, yielding a half-life of 7.7 ± 3.0 min. The conclusion from these data is that either (i) there is a new γ-decaying isomer in ^{177}Hf, or (ii) there is a previously unreported β-decaying isomer in ^{177}Lu.

The Si-detector spectra displayed in Fig. 18 support the scenario of β decay from a ^{177}Lu^{m2} level. The upper panel shows the electron events in the Si detector gated by the 89 keV transition in the Ge detector. As expected, there is no strong electron-conversion component associated with the 1003 keV transition (see upper panel of Fig. 18.) Rather there is a distribution of low-energy events above the energy threshold of ≈ 140 keV, suggesting a population via β decay. By contrast, the lower panel of Fig. 18 gives an example of known low-energy discrete electron-conversion (K and L) transitions that were recorded in the Si detector and are associated with transitions in ^{177}Yb from an excited state [38]. If we consider the hypothesis of a ^{177}Lu β decay to be correct, then the β end point (in coincidence with the 89 keV γ-ray transition) is evidently no more than 650 keV (see Fig. 18, upper panel) and most of the β particles would have energies below the detection threshold of the electron detec-

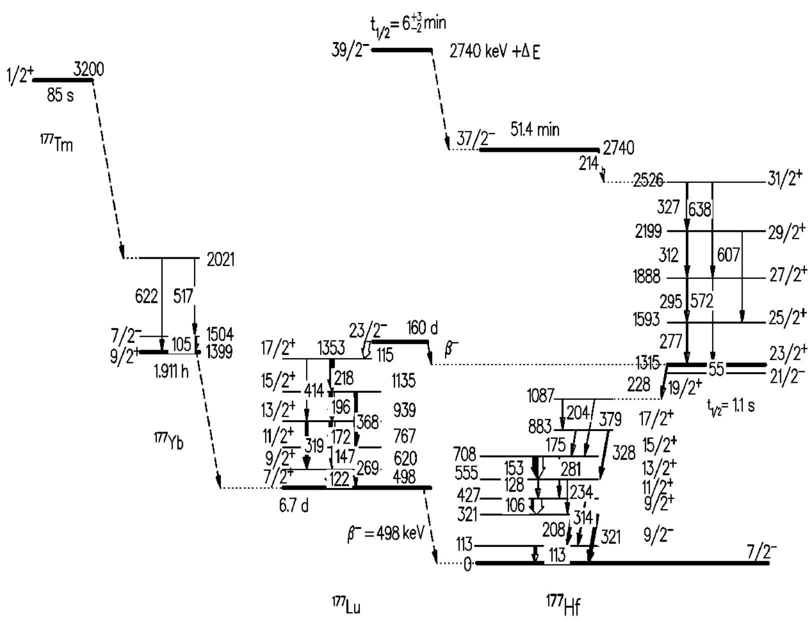

FIG. 13. Partial decay schemes for ^{177}Lu and ^{177}Hf showing the previously reported isomeric states and the candidate isomer with $K^\pi = 39/2^-$ in ^{177}Lu (all energies are given with respect to the $7/2^-$ ground state of ^{177}Hf) [6,39,44,45,47,48,53,54]. The ground-state decays for ^{177}Tm and ^{177}Yb are also shown for completeness.

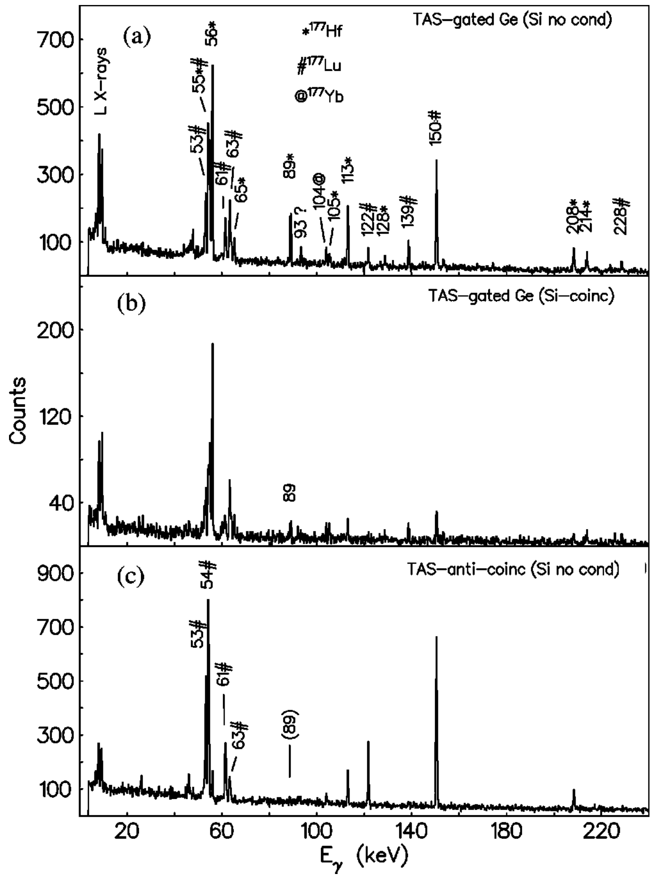

FIG. 14. γ-ray spectra recorded for $A=177$ by the small Ge detector at the TAS station, with a 1200 s tape period and a tantalum target. The strongest previously unreported transition at 89 keV is observed in TAS coincidence (upper panel). It is also observable in coincidence with the Si detector (middle panel) but absent in the TAS anticoincidence spectrum (lower panel). The 53–56 keV transitions are K_α x rays for hafnium and ytterbium, and the 61–65 keV transitions are the corresponding K_β x rays.

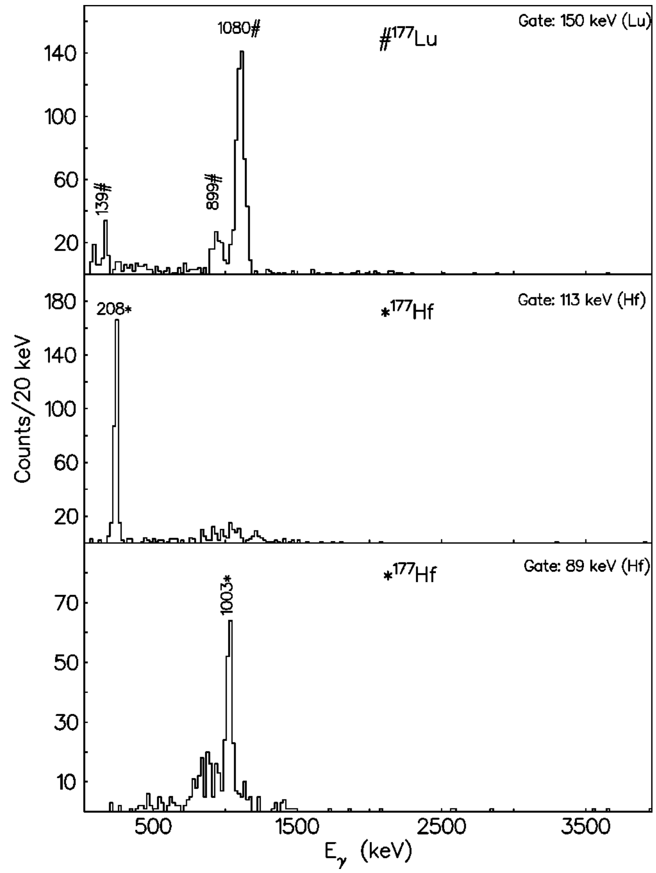

FIG. 15. γ-ray spectra recorded at $A=177$ by the TAS, in coincidence with different transitions observed in the Ge detector. The tape-cycle period was 1200 s and the data were taken using a tantalum target. The lower panel is of principal interest, showing coincidences with the previously unobserved 89 keV transition. The energies indicated in the upper two panels correspond (with ±4 keV uncertainties) to well-known γ-ray transitions in ^{177}Hf [44,45] and ^{177}Lu [38].

tor. Note that the significantly different measured decay γ-ray intensities of the 89 keV transition and the much stronger 214 keV line which depopulates the $\frac{37}{2}^-$, $t_{1/2}=51$ min isomer in ^{177}Hf (see Table III) are consistent with significant *direct* β-decay feeding to this state from the proposed higher-lying isomeric state.

Figure 19 shows the proposed partial decay scheme for the two newly identified transitions (89 and 1003 keV) in ^{177}Hf, following the β decay of the proposed $K^\pi=39/2^-$ isomer in ^{177}Lu. The displayed spectrum in the lower panel of Fig. 15 is most easily explained by using the scheme shown in Fig. 19, with implied partial β^- feeding through other (unobserved) γ-ray transitions with energies less than 1003 keV. This explanation is supported by the intensity measurements for the 89 keV transition following the β decay of the proposed ^{177}Lu, $K^\pi=39/2^-$ isomer, and for the 214 keV transition following the internal decay of the $K^\pi=37/2^-$ isomer in ^{177}Hf. The relative intensity measurements are given in Table III.

Gating on the 1003 keV transition in the TAS does not yield any significant coincident events in the Si detector, which means that there is no evidence for direct β-decay branch to the intermediate state. However, the absence of this decay could be due to the poor statistics or could imply that the β transition is forbidden by spin/parity selection rules. The spin and parity assignments are discussed in the following section.

It is also worth noting that the half-life determined for the population of the 89 keV transition, as observed by the small Ge detector in the TAS experiment ($t_{1/2}=7.7\pm3.0$ min), is consistent with that obtained from the Cluster experiment for the first component, 6^{+3}_{-2} min, of the two-component "grow-in" curve for ^{177}Hf^{m2}.

The placement of the proposed ^{177}Lu $K^\pi=39/2^-$ isomer depends on the various factors, presented above, being consistent with such an isomer populating the 51 min ^{177}Hf^{m2} $K^\pi=37/2^-$ state, at an energy of 2740 keV (relative to the ^{177}Hf ground state.) If the isomer were of lower angular momentum, it would be difficult to understand why no coincidences with previously reported γ-ray transitions in ^{177}Hf [52,49] were observed in our measurement. Recall also that the 7.7 min isomer must decay into a hafnium isotope from the x-ray evidence of Fig. 16, and must have $A=177$, from

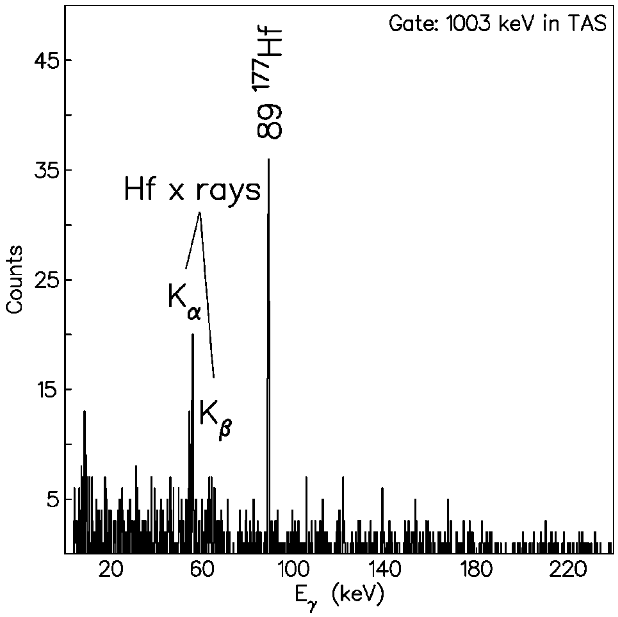

FIG. 16. γ-ray spectrum recorded in the small-volume Ge detector spectrum for $A=177$, using a tantalum target, a 1200 s tape cycle, a coincidence condition on the 1003 keV transition in the TAS spectrum, and a subtraction of a similar range of an adjacent "background" region. The previously unreported 89 keV transition and the hafnium x-ray peaks are clearly identified.

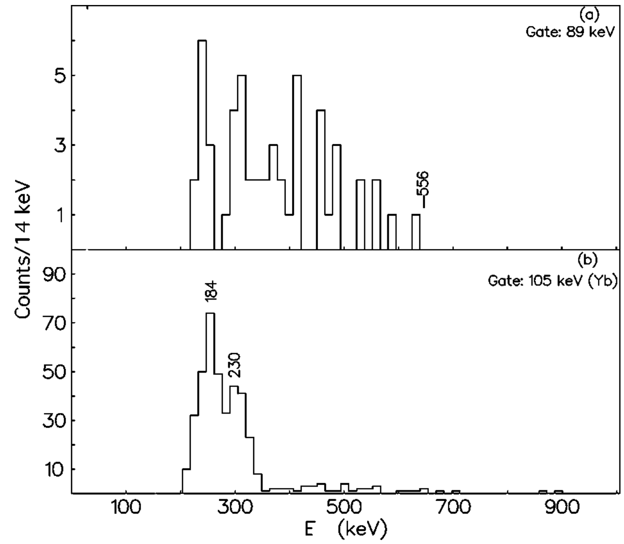

FIG. 18. Electron spectra recorded at $A=177$ by the Si detector in the TAS experiment in coincidence with (a) 89 keV γ rays measured in the germanium detector (tape period 1200 s, tantalum target) and (b) 105 keV γ rays in Yb (tape period 16 s, ^{186}W target). The γ rays used for the coincidence conditions were measured by means of the small Ge detector, the 105 keV transition representing a known transition in ^{177}Yb (see Fig. 13). The candidate electron energies are indicated with their energies in keV, taking into account the detector threshold of $\approx$140 keV and hafnium and ytterbium K- and L-binding energies of 65 and 61 keV, and 11 and 10 keV, respectively.

the mass-separator setting. All of these features can be considered as experimental evidence for the observation of a β^--decaying isomer corresponding to the calculated state with $K^\pi=39/2^-$ in ^{177}Lu (see the following section).

The excitation energy of the proposed $39/2^-$ isomer in ^{177}Lu can be estimated by summing the 89 and 1003 keV energies with 2740 keV for ^{177}Hf^{m2}, adding $\approx$600 keV for the β-decay energy (Fig. 18) and subtracting $\approx$500 keV for the ^{177}Lu ground-state Q_β value [52], yielding an excitation energy of $\approx$3.9 MeV in ^{177}Lu. Although this is higher than the calculated value of 2.7 MeV (see the following section and Fig. 20), it nevertheless seems to provide the most logical explanation of the observed data. The resulting level structure is illustrated in Fig. 19.

(We note that none of the transitions identified in the current work coincide with those reported by Mullins *et al.* [49]. This may reflect the difference in the population mechanisms for the two studies.)

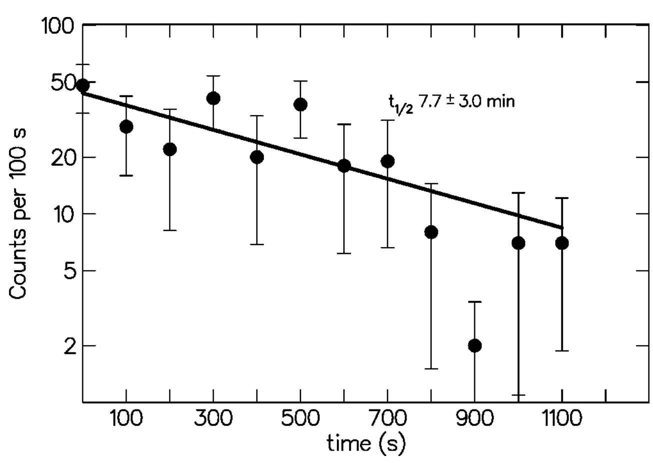

FIG. 17. Decay data for the intensity of the 89 keV transition deduced from the γ-ray spectrum measured by operating the small Ge detector in coincidence with the TAS. Also shown is the result obtained from a fit assuming a single-component exponential decay which yields a half-life of 7.7 ± 3.0 min.

IV. THEORETICAL DISCUSSION

Nilsson model calculations

Nilsson model calculations, with blocked BCS pairing [9], have indicated that there are good prospects for finding a number of favored, high-K states throughout the $A\sim180$ region [1,9,10]. Blocked BCS calculations for ^{177}Lu, performed with deformation parameters of $\epsilon_2=0.261,\epsilon_4=0.046$ [8], together with monopole pairing parameters of $G(n)$

TABLE III. Comparison of the intensities (arbitrary units) for the 89 and 214 keV transitions attributed to ^{177}Hf from the newly proposed 7.7 min and the previously reported $t_{1/2}=51.4$ min isomers [6,38] in ^{177}Lu and ^{177}Hf, respectively. The tape-cycle period was 1200 s.

E (keV)	Nucleus	$I_{arb\ unit}$	$t_{1/2}$ (min)
89	^{177}Lu	2.2(2)	7.7
214	^{177}Hf	23.7(9)	51.4

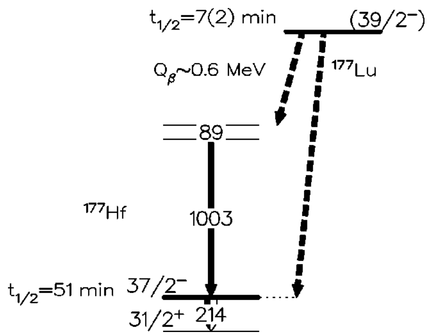

FIG. 19. Proposed partial level scheme associated with the $t_{1/2}$ $=7.7$ min isomer in ^{177}Lu. The dashed lines represent the possible direct β-decay transitions.

$=21.50/A$ MeV and $G(p)=22.50/A$ MeV [9], are shown in Fig. 20. These calculations predict an energetically favored state which is consistent with the well established K^{π} $=23/2^{-}$ β-decaying isomer ($t_{1/2}=160$ days) [47,48]. The predicted excitation energy of $E_x=1.0$ MeV is in excellent agreement with the observed value of 0.97 MeV. This isomeric state decays by both external β^{-} (78%) and internal γ rays and internal conversion (22%) branches [47]. It has been suggested that the Nilsson configuration of the K^{π} $=23/2^{-}$ isomer in ^{177}Lu is a three-quasiparticle arrangement comprising $\pi\frac{7}{2}^{+}[404]\otimes\nu\{\frac{9}{2}^{+}[624]\otimes\frac{7}{2}^{-}[514]\}$ [48]. Notably, this is the same configuration as that predicted by the blocked BCS calculations.

The configuration-constrained potential energy surface (PES) obtained by the method described in Ref. [10] for the $K^{\pi}=37/2^{-}$ isomeric state in ^{177}Hf is shown in Fig. 21. In light of the previous discussion of a possible β^{-}-decaying isomer feeding this state, it is interesting to note that the blocked BCS calculations also predict an energetically favored higher lying five-quasiparticle state with $K^{\pi}=39/2^{-}$ in

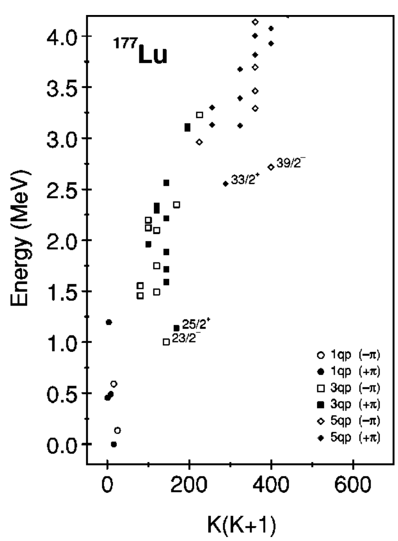

FIG. 20. Blocked BCS calculation for the energies of the near-yrast multi-quasiparticle states in ^{177}Lu nucleus with pairing strengths of $G(n)=21.50/A$ MeV and $G(p)=22.50/A$ MeV and deformation parameters of $\epsilon_2=0.261$ and $\epsilon_4=0.046$ [8] (see text for details).

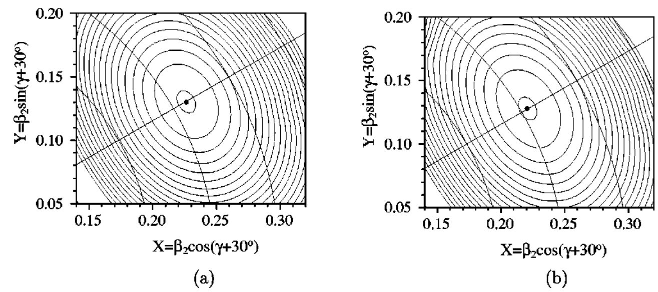

FIG. 21. Configuration-constrained PES calculations for (a) the previously reported yrast five-quasiparticle $K^{\pi}=37/2^{-}$ state in ^{177}Hf. The minimum is associated with quadrupole deformation parameters $(\beta_2,\gamma)=(0.261,0°)$ and a hexadecapole deformation parameter $\beta_4=-0.047$. (b) The predicted $K^{\pi}=39/2^{-}$ state in ^{177}Lu, with the minimum at $(\beta_2,\gamma)=(0.255,0°)$ and $\beta_4=-0.046$. Both calculations use Lipkin-Nogami pairing and a deformed Woods-Saxon potential.

^{177}Lu. The predicted Nilsson configuration for this state is $\pi\{\frac{7}{2}^{+}[404]\otimes\frac{9}{2}^{-}[514]\otimes\frac{7}{2}^{-}[523]\}\otimes\nu\{\frac{7}{2}^{-}[514]\otimes\frac{9}{2}^{+}[624]\}$. The corresponding PES for this configuration is shown in Fig. 21.

The population of such a state would be consistent with the observed results for the ^{177}Hf isomer if there was a ΔK $=1$, β^{-} decay (which could proceed via an allowed Gamow-Teller decay), between the predicted $K^{\pi}=39/2^{-}$ state in ^{177}Lu and the well established $K^{\pi}=37/2^{-}$ ($t_{1/2}=51.4$ min) isomer in ^{177}Hf. The suggested Nilsson configuration of the $K^{\pi}=37/2^{-}$ state in $^{177}_{72}$Hf is $\pi\{\frac{7}{2}^{+}[404]\otimes\frac{9}{2}^{-}[514]\}$ $\otimes\nu\{\frac{7}{2}^{-}[514]\otimes\frac{9}{2}^{+}[624]\otimes\frac{5}{2}^{-}[512]\}$ [39]. This would be consistent with the proposed β^{-} decay from the $K^{\pi}=39/2^{-}$ state in $^{177}_{71}$Lu proceeding via transforming the configuration from $\pi\frac{7}{2}^{-}[523]\rightarrow\nu\frac{5}{2}^{-}[512]$.

For this to be a valid explanation, the internal electromagnetic decay within ^{177}Lu from the proposed $K^{\pi}=39/2^{-}$ state must be highly hindered, otherwise one would expect that it should also have been observed in the current work. The calculations shown in Fig. 20 suggest that the next lowest-energy intrinsic state ($K^{\pi}=33/2^{+}$) lies just below the K^{π} $=39/2^{-}$ state. A simple parity changing, $\Delta K=3$ spin difference between these two states would be unlikely to produce such a transition (i.e., an $E3$ transition), long enough lived for β^{-} decay to compete with γ-ray emission. However, if the predicted $K^{\pi}=33/2^{+}$ state lies closer to, or even above, the predicted $K^{\pi}=39/2^{-}$ state, the latter may form a yrast trap, which subsequently decays to states built on the K^{π} $=23/2^{-}$ state ($\Delta K=8$) or the predicted $25/2^{+}$ state ($\Delta K=7$). Note that, to date, no rotational transitions built on the K^{π} $=23/2^{-}, t_{1/2}=160$ day isomer have been reported in the literature. In this way, the lack of internal ^{177}Lu decays are interpreted here to be a consequence of the conservation of the K quantum number, with large-ΔK transitions being highly retarded [50]. In contrast, the β decay to ^{177}Hf is interpreted as being "K allowed," with $\Delta K=1$. Since the γ decay is K inhibited, it could be said that the β decay is "K driven."

TABLE IV. Decay properties of the two possible β transitions from the proposed $K^{\pi}=39/2^{-},t_{1/2}=7.7$ min isomer in ^{177}Lu. The well-known $K^{\pi}=23/2^{-}$ isomer, and the ground-state β decays in ^{177}Lu are also given for reference (see text for details).

$I_i^{\pi}(\hbar)$	E_{β^-} (keV)	$t_{1/2}^{partial}$	log ft (This work)	log ft (Published)
$\frac{39}{2}^{-}(\beta_1)$	~600.0	77.0 min	4.70	
$\frac{39}{2}^{-}(\beta_2)$	~1700.0	8.6 min	5.30	
$\frac{23}{2}^{-}$	153	205 days	6.40	6.30
$\frac{7}{2}^{+}$	498.2	8.6 days	6.7	6.5

1. Analysis of logft values

One of the approaches to investigate the permissibility of any β decay is to calculate the log ft value of the particular transition and see how hindered or allowed it is. The log ft value [51] is determined by the partial half-life, the decay energy E_{β^-} of the transition, and the atomic number of the daughter nucleus. Table IV presents the log ft values for the ^{177}Lu β-decay feeding into the $K^{\pi}=37/2^{+}$ isomer through the 89 and 1003 keV transitions (marked as β_1), in addition to the other (possible) direct β feeding to the $37/2^{-}$ isomer (β_2) The log ft values for the well-known $K^{\pi}=23/2^{-}$ isomer and the ^{177}Lu ground state have been calculated and agree with the published values [52].

2. Spin and parity assignments

To assign the spins and parities for the states depopulating via the 89 and 1003 keV transitions, the log ft value for the state decaying by the 89 keV transition has been calculated (see Table IV.) The calculated value is indicative of an allowed transition which means no parity change. For the 89 keV decay, the experimental α_K value of 0.42 ± 0.15 is consistent only with the theoretical value for an electric dipole decay (see the preceding section). This assignment then also constrains the 1003 keV transition to have $E1$ character in order to terminate at the $K^{\pi}=37/2^{-},t_{1/2}=51$ min isomer.

V. SUMMARY AND CONCLUSIONS

We have presented the results obtained in two experiments using collisions between a ^{136}Xe beam with tungsten and tantalum targets and on-line mass separation with the aim of identifying new, high spin isomers in neutron-rich nuclei with $A\approx180$. In the first experiment γ rays associated with the decay of the well established $K^{\pi}=37/2^{-},t_{1/2}=51.4$ min isomer in ^{177}Hf were observed with an unexpectedly high yield and an apparent difference in the measured half-life ($t_{1/2}=76^{+16}_{-9}$ min) compared to the published value. These phenomena are presented as potential evidence for a higher-lying, β-decaying isomeric state in ^{177}Lu which populates the $K^{\pi}=37/2^{-}$ state in ^{177}Hf.

If the second, lower-lying component is fixed at the published value of 51.4 min, a two-component half-life analysis of the ^{177}Hf γ rays following the decay of the $K^{\pi}=37/2^{-}$ isomer gives an estimate of 6^{+3}_{-2} min for the shorter-lived component. This agrees well with the half-life of 7.7 ± 3.0 min observed in the TAS experiment. The weighted average half-life for both experiments is 7 ± 2 min. Both scenarios are consistent with the multi-quasiparticle and PES calculations which predict a favored $K^{\pi}=39/2^{-}$ five-quasiparticle state in ^{177}Lu.

ACKNOWLEDGMENTS

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