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Nuclear structure of ^{178}Lu

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The ^{179}Hf$(t,\alpha)^{178}$Lu reaction has been studied using beams of 17 MeV tritons from the McMaster University tandem Van de Graaff accelerator. Reaction products were analyzed with a magnetic spectrograph, and the resolution achieved for the alpha spectra was ~20 keV (FWHM). Two-quasiparticle states in ^{178}Lu involving the $9/2^+[624]$ target neutron coupled with the $7/2^+[404]$, $9/2^-[514]$, and $1/2^+[411]$ proton orbitals were identified. The difference in ground-state (t,α) Q values for ^{178}Hf and ^{179}Hf components of the target, combined with the known masses of ^{177}Lu, ^{178}Hf, and ^{179}Hf, yields an improved value of $-50\,351 \pm 5$ keV for the mass excess of ^{178}Lu. This result, combined with the two-quasiparticle assignments from the present work, has resolved the long-standing puzzle concerning the character and excitation energy of the well-known 23 min high-spin beta-decaying isomer in ^{178}Lu.

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I. INTRODUCTION

The doubly odd deformed nucleus $^{178}_{71}$Lu$_{107}$ is interestingly located, being isotonic with nature's rarest "stable" nuclide ^{180}Ta and isotopic with the next longest-lived odd-odd deformed nucleus ^{176}Lu. Both these "exotic" nuclei have been extensively studied [1,2] over the past several years. These investigations have resulted in the identification of various intrinsic and rotational structures expected in their $(Z,N) = (71,107)$ neighbor. However, the level structure of ^{178}Lu remains almost unexplored even today [3]. A number of investigators [3–7] have reported long-lived ^{178}Lu isomers, with half-lives ranging from 5 to 30 min, from ^{179}Hf(γ,p), ^{181}Ta(n,α), ^{178}Hf(n,p), ^{176}Yb(t,n), and ^{176}Yb(α,np) reaction studies. Out of these, only a 23 min high-spin isomer is firmly established through its well-studied [4–7] beta decay to high-spin levels in ^{178}Hf. This isomer decay provided possibly the earliest experimental evidence for ΔK=0 mixing in high-spin bands of even-mass nuclei. However, the energy of this isomer remains very poorly defined due to the nonobservation of any isomeric transition to lower-lying levels in ^{178}Lu, and large uncertainties in the $Q(\beta^-)$ values for both the 28 min ground state and the 23 min isomer decays. There is conflicting evidence concerning the spin-parity assignment of the isomer. Beta-decay properties [6,7] indicate it is I^π=9^- but the most recent Nuclear Data Sheets [3] show an I^π=7^- level at a lower energy, which is inconsistent with the observed long half-life. The known 7^- level is the K^π=7^- $\{7/2^+[404]_\pi + 7/2^-[514]_\nu\}$ bandhead populated in ^{176}Lu(t,p) studies [8]. The energy of this level relative to the unobserved ground state had an uncertainty of ±40 keV, arising from the uncertainty in the mass value for ^{178}Lu.

The only two levels with well-defined energies, at 42.4 keV and 390.8 keV, were identified in gamma decays following the ^{178}Yb beta decay [5]. While the 42 keV level is interpreted [3,5] as the I^π=2^+ rotational level of the K^π=1^+ ground-state band, which was assigned the $\{9/2^+[624]_\nu - 7/2^+[404]_\pi\}$ configuration, a two-quasiparticle (2qp) state with structure K^π=1^+ $\{9/2^-[514]_\pi - 7/2^-[514]_\nu\}$ has been suggested [9] for the 391 keV level from logft considerations.

Against this background, the present work reports results of a ^{179}Hf(t,α) reaction study of ^{178}Lu levels. This reaction populates various 2qp structures arising from coupling the $9/2^+[624]$ target neutron with different proton orbitals available around the Z=71 Fermi surface. The analysis and interpretation of these results was aided considerably by the availability of data on the neighboring isotopes ^{177,179}Lu, obtained from ^{178,180}Hf(t,α) reaction studies [10] performed in this laboratory under the same experimental conditions as the present work. The experiment reported here yields a more precise value for the ^{178}Lu atomic mass and also provides a satisfactory solution of the puzzle concerning the character and excitation energy of the 23 min isomer.

The experimental details and results are presented in

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Sec. II and an analysis of these results and their interpretation in terms of 2qp structures is included in Sec. III. Section IV shows how these results resolve the previous conflicting interpretations for the high-spin 23 min isomer and how the available data on ^{178}Lu levels can now be explained consistently.

II. EXPERIMENTAL DETAILS AND RESULTS

The present measurements were made with the same experimental setup and techniques as for the ^{178,180}Hf$(t,\alpha)^{177,179}$Lu results reported earlier [10]. Therefore, only a brief description will be given here. The target was prepared from a sample of HfO$_2$, enriched to 81.85% ^{179}Hf, purchased from the Stable Isotopes Division of the Oak Ridge National Laboratory. The oxide was reduced with magnesium metal using a procedure developed by Peng [11], and the hafnium metal was vacuum evaporated onto a 40 μg/cm^2 carbon foil. The thickness of the hafnium layer, as determined from intensities of elastic scattering during the present measurements, was ~120 μg/cm^2.

The experiments were performed using beams of 17 MeV tritons from the McMaster University tandem Van de Graaff accelerator, and the reaction products were analyzed with the Enge split-pole magnetic spectrograph. For most of the spectra, the particles were detected by a position-sensitive silicon surface-barrier detector, which had a length of 58 mm, located in the focal plane. This detector length corresponded to a range of ~1.4 MeV of excitation energy. Measurements were made at θ=12° and in 5° intervals from θ=15° to 45°. Spectra were also recorded at θ=45° and θ=60° using photographic plates as detectors, which give more reliable values for excitation energies since the spectrograph calibration is known more accurately for plates. The resolution was ~20 keV (full width at half maximum) for all of the measurements. Figure 1 shows the ^{179}Hf$(t,\alpha)^{178}$Lu spectrum at θ=45° obtained with photographic plates.

Cross sections were determined by comparing intensities of peaks in the alpha spectra with the numbers of elastically scattered tritons detected in a silicon surface-barrier monitor detector mounted in the target chamber at 30° to the incident beam. The solid angles of the monitor detector and the spectrograph were known, and the elastic scattering cross section at 30° was assumed to be 4750 mb/sr (~89% of the Rutherford value) as obtained from optical model calculations described below. The levels populated in ^{178}Lu are listed in Table I, which also shows the cross sections at θ=25°. The interpretations given for levels in Table I are discussed in the following section. Angular distributions for the (t,α) cross sections of some ^{178}Lu levels are shown in Fig. 2.

In the 1986 mass tables [12] the uncertainty on the ^{178}Lu mass is 24 keV, and a more precise value can be obtained from Q value differences measured in the present work. According to the supplier of the ^{179}Hf sample, there were isotopic impurities of 5.42% ^{178}Hf and 8.74% ^{180}Hf in the target, and peaks resulting from these impurities can be seen in the spectrum of Fig. 1. From the mass tables [12] the difference of ground-state Q values $Q[^{178}\text{Hf}(t,\alpha)] - Q[^{179}\text{Hf}(t,\alpha)]$ is expected to be 85 ± 25 keV, and the present measurements yield a value

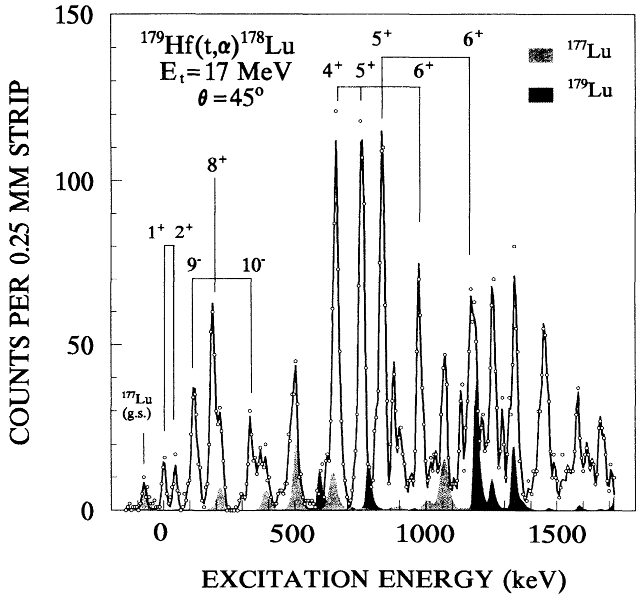

FIG. 1. Spectrum of alpha particles from the ^{179}Hf$(t,\alpha)^{178}$Lu reaction at θ=45°. Rotational bands shown correspond to two-quasiparticle structures listed in Table I and discussed in the text. Contributions from the ^{177}Lu and ^{179}Lu impurities are shown, respectively, by lighter and darker shaded areas.

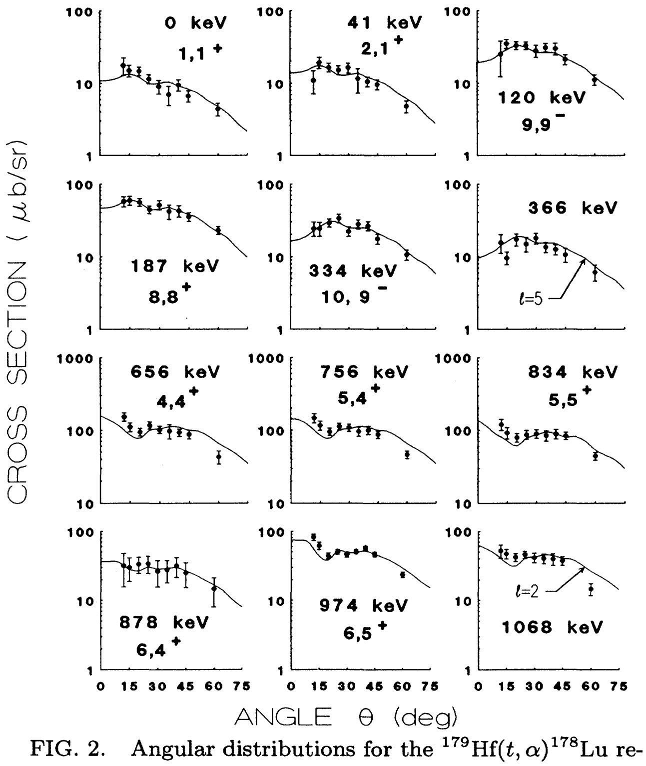

FIG. 2. Angular distributions for the ^{179}Hf$(t,\alpha)^{178}$Lu reaction. The curves shown with the data points are DWBA calculations for the configurations as assigned in the present study and listed in Table I.

of 72 ± 2 keV. When this result is combined with the adopted masses [12] for ^{177}Lu, ^{178}Hf, and ^{179}Hf, an improved value of $-50\,351 \pm 5$ keV is obtained for the mass excess of ^{178}Lu. This is consistent with, but more precise than, the previously adopted value of $-50\,338 \pm 24$ keV.

III. CALCULATIONS AND INTERPRETATION

A. Outline of the procedure

The approach used in the analysis of the present results is similar to that taken in a number of previous studies of well-deformed odd-odd nuclides by the use of single-nucleon-transfer reactions [13–17]. In general, the transition populating each final state contains a mixture of j and l values and it is not possible in practice to extract the spectroscopic strength for each j value from the experimental angular distributions. Thus it is more appropriate to compare observed cross sections with the predicted values.

The cross section for pickup of a single nucleon, leading to a rotational band member of spin I_f in an odd-odd deformed nucleus can be written [13,15]

$$\frac{d\sigma}{d\Omega} = N\sum_{j,l}\left[\sum_{i} a_i(C_{jl})_i V_i \langle I_o K_o j \Delta K \mid I_f K_f\rangle\right]^2 \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{DW}}, \qquad (1)$$

where N is a normalization constant for the distorted wave Born approximation (DWBA) cross sections, $(d\sigma/d\Omega)_{\mathrm{DW}}$. The C_{jl} values are expansion coefficients describing the Nilsson orbital of the transferred nucleon. The Clebsch-Gordan coefficient couples the odd target nucleon I_o, K_o with the transferred $j, \Delta K$ to form the final state I_f, K_f, and V^2 is the occupation probability in the target for the transferred nucleon. The final state is

TABLE I. Levels populated in the ^{179}Hf$(t,\alpha)^{178}$Lu reaction.

Excitation energy (keV)		Cross section[c] (μb/sr)	Interpretation
Previous[a]	Present[b]	θ=25°	I,K^π, $\Omega^\pi[Nn_3\Lambda]_\nu \pm \Omega^\pi[Nn_3\Lambda]_\pi$
0	0	12	$1,1^+$, $9/2^+[624]-7/2^+[404]$
42.4	41(1)	15	$2,1^+$, $9/2^+[624]-7/2^+[404]$
	96(4)	~11	($3,1^+$, $9/2^+[624]-7/2^+[404]$)?
	120(3)	33	$9,9^-$, $9/2^+[624]+9/2^-[514]$
	187(1)	44	$8,8^+$, $9/2^+[624]+7/2^+[404]$
	215(3)	18[d]	
	300(4)	5	($5,1^+$, $9/2^+[624]-7/2^+[404]$)?
	334(2)	33	$10,9^-$, $9/2^+[624]+9/2^-[514]$
	366(3)	15	
	475(4)	8	
	499(2)	16[e]	($7,7^+$, $9/2^+[624]+5/2^+[402]$)?
	656(2)	106	$4,4^+$, $9/2^+[624]-1/2^+[411]$
	756(2)	112	$5,4^+$, $9/2^+[624]-1/2^+[411]$
	834(2)	86	$5,5^+$, $9/2^+[624]+1/2^+[411]$
	878(2)	34	$6,4^+$, $9/2^+[624]-1/2^+[411]$
	906(3)	15	
	974(2)	50	$6,5^+$, $9/2^+[624]+1/2^+[411]$
	1033(3)	18	
	1068(2)	46	
	1133(2)	33	
	1167(3)	~50	
	~1186?	~25[f]	
	1215(3)		
	1255(2)		
	1290(3)		
	1341(2)		

[a] Previous energies are from Nuclear Data Sheets [3].

[b] Values in parentheses are uncertainties in keV.

[c] Uncertainties in the relative cross sections for large well-resolved peaks are ~10%. For absolute values the uncertainties are ~20%.

[d] Value obtained after subtracting 8 μb/sr expected for known ^{178}Hf$(t,\alpha)^{177}$Lu impurity peak.

[e] Value obtained after subtracting 17 μb/sr expected for known ^{178}Hf$(t,\alpha)^{177}$Lu impurity peak.

[f] Most of this cross section is due to a known ^{180}Hf$(t,\alpha)^{179}$Lu impurity peak, but at several angles there is excess intensity indicating the possible presence of a level here.

assumed to be a Coriolis-mixed configuration, with amplitudes a_i for the various Nilsson orbitals from which the transferred nucleon may be picked up.

The single-particle cross sections $(d\sigma/d\Omega)_{\rm DW}$ were calculated with the computer program [18] DWUCK4, using the same optical model parameters as in a recent (t,α) study [10] of ^{177,179}Lu levels. Experience with the (t,α) reaction in this mass region has shown that the strong transitions have l values of 2, 4, or 5, since the available Nilsson proton orbitals originate from the $2d_{3/2}$, $2d_{5/2}$, $1g_{7/2}$, or $1h_{11/2}$ shell model states. With the triton beam energy available, the (t,α) angular distributions for l=4 and l=5 are rather similar, so that even under the most favorable conditions it can be difficult to distinguish between them from the experimental data. However, it is usually possible to distinguish an l=2 angular distribution from one with $l \geq 4$. Although, in principle, each transition can have a mixture of j and l values, it is found in practice that one j,l combination often dominates because each Nilsson proton orbital in this region tends to have large C_{jl} coefficients for only one value of j. Thus, in many cases, the experimental angular distributions for strong peaks can indicate whether the proton was picked up from an orbital dominated by l=2, or $l \geq 4$.

In the following subsections the assignments of experimentally observed levels in terms of Nilsson model 2qp states will be discussed. All cases involve the unpaired $9/2^+[624]$ neutron of the ^{179}Hf target coupled with a proton left unpaired after the (t,α) reaction. Coriolis-mixing calculations were performed for the final 2qp configurations, and the predicted (t,α) cross sections before and after mixing are compared with experimental values in Table II. These calculations started with wave functions from a Nilsson calculation with deformation δ=0.3, the standard values of κ=0.0637 and μ=0.600 for protons in this mass region, and pairing factors V^2 similar to those used [10] for states in the odd-mass neighbors ^{177,179}Lu. The spirit of these calculations was to use reasonable parameter values from earlier studies in this mass region to obtain an approximate indication of the effects that Coriolis mixing would have, rather than to vary many parameters in an attempt to obtain the best fit to the observed energies and cross sections. Thus, the only parameters varied were the input values for the bandhead energies of the unmixed states. Cross sections were then calculated from the wave functions of the initial and the mixed states. These are listed in Table II and are discussed for the various configurations in the following subsections.

B. $K^\pi = 1^+$ $\{9/2^+[624]_\nu - 7/2^+[404]_\pi\}$ ground-state configuration

The ground state of ^{178}Lu was previously suggested [3] as this K^π=1$^+$ configuration with the I=2 rotational member at 42.4 keV. The first two peaks attributed to ^{178}Lu in the spectrum of Fig. 1 can be associated with these levels. Their energy separation from the well-known ^{178}Lu$(t,\alpha)^{177}$Lu ground-state transition seen as an impurity peak in Fig. 1 was used to determine the Q value difference quoted in Sec. II above.

The observed cross sections at θ=25° are compared with predicted values in Table II. It is seen that for this band the strength is expected to be distributed over many levels and thus none of them should be populated strongly. The observed cross sections in Table II and the angular distributions shown in Fig. 2 for the 1$^+$ ground state and the 41 keV 2$^+$ state are in reasonable agreement with predictions for such weak transitions.

A K^π=1$^+$ band with the same 2qp configuration has been observed [1] as the ground-state band in the isotonic neighboring nucleus ^{180}Ta, in which the experimental excitation energies for various I^π members of the band are 1$^+$, 0 keV; 2$^+$, 42 keV; 3$^+$, 111 keV; 4$^+$, 187 keV; and 5$^+$, 309 keV. Noticing the same energies for the two lowest levels, and hence the same moment of inertia, for this band in both nuclei, it is reasonable to expect similar excitation energies for the higher-spin levels of this band in ^{178}Lu as well. As it happens, a much larger peak for another level at ~120 keV (discussed below) obscures the expected peak for the 3$^+$ level. There is, however, evidence for a small peak at ~96 keV in the spectra at most angles, which is a possible candidate for the 3$^+$ band member. The transition for the 4$^+$ level would be obscured by the much larger peak in the spectrum at 187 keV. A weak peak at ~300 keV can be considered a candidate for the 5$^+$ member of this band, but this suggestion is considered to be speculative.

C. $K^\pi = 8^+$ $\{9/2^+[624]_\nu + 7/2^+[404]_\pi\}$ configuration

As the $7/2^+[404]$ proton orbital originates from the $1g_{7/2}$ shell it has a large C^2_{jl} value only for j=7/2. Thus, when it is coupled parallel with the $9/2^+[624]$ neutron to form a K^π=8$^+$ band, virtually all of the transfer strength must be concentrated in the I=8 bandhead. This can be seen in Table II, where the I=9 cross section is predicted to be negligibly small. As a result, the 8$^+$ bandhead is expected to have the largest peak with $l \geq 4$ in the low energy region of the spectrum. In fact, the only peak which is large enough to be consistent with this 8$^+$ level is the one at 187 keV. It is seen from Table II and Fig. 2 that the absolute intensity and the angular distribution are in excellent agreement with predictions. The only other strong peaks in the low energy region of the spectrum are the ones for levels at 120 keV and 334 keV. However, these are not likely candidates for the I^π=8$^+$ level considered here, because they are weaker than expected and their spacing makes them the only reasonable prospects for the 9$^-$ and 10$^-$ members of a K^π=9$^-$ band discussed in the next subsection. This assignment for the K^π=8$^+$ band also gives a Gallagher-Moszkowski (GM) splitting which is similar to that observed in the isotone ^{180}Ta. The energy splitting between the K^π=1$^+$ and K^π=8$^+$ bandheads is 187 keV in ^{178}Lu, compared with 177 keV in ^{180}Ta.

It is noted that in the (t,α) studies [10] of ^{177,179}Lu the cross sections for transfer of the $7/2^+[404]$ proton to form the ground states were ~90 μb/sr at θ=25° in both nuclides. In the present case, which has a similar Q

TABLE II. Comparison of observed and predicted (t,α) cross sections for ^{178}Lu levels.

Configuration	Energy (keV)	Cross section (μb/sr), θ=25°		
		Unmixed[a]	Mixed[b]	Experimental[c]
$9/2^+[624]_\nu\pm7/2^+[404]_\pi$				
$K^\pi=1^+$, $I=1$	0	13.5	13.5	12
2	42	14.4	14.4	15
3	(96)	10.1	10.3	~11
4		5.1	5.2	
5	(300)	1.8	1.9	5
6		0.4	0.5	
$K^\pi=8^+$, $I=8$	187	44.6	45.0	44
9		0.4	0.3	
$9/2^+[624]_\nu\pm9/2^-[514]_\pi$				
$K^\pi=9^-$, $I=9$	120	16.8	22.8	33
10	334	19.7	26.4	33
$K^\pi=0^-$, $I=0$		0.0	0.0	
1		1.7	1.8	
2		5.8	6.5	
3		9.1	11.5	
4		9.0	13.2	
5		6.1	10.8	
6		1.0	6.5	
7		0.2	2.8	
8		0.1	0.8	
$9/2^+[624]_\nu\pm5/2^+[402]_\pi$				
$K^\pi=7^+$, $I=7$	(499)?	16.1	19.4	(16)?
8		0.4	0.4	
$K^\pi=2^+$, $I=2$		8.0	7.9	
3		5.3	6.9	
4		2.4	4.0	
5		0.8	2.6	
$9/2^+[624]_\nu\pm1/2^+[411]_\pi$				
$K^\pi=4^+$, $I=4$	656	64.1	64.9	106
5	756	38.1	68.4	112
6	878	13.0	24.1	34
7		2.8	4.7	
8		0.4	0.6	
$K^\pi=5^+$, $I=5$	834	75.5	44.6	86
6	974	35.5	33.4	50
7		7.6	15.1	
8		1.0	2.1	
$9/2^+[624]_\nu\pm3/2^+[411]_\pi$				
$K^\pi=6^+$, $I=6$		85.1	75.8	
7		52.9	37.4	
8		4.2	2.5	
$K^\pi=3^+$, $I=3$		50.1	47.2	
4		53.0	49.3	
5		28.9	26.4	
6		9.3	8.4	
7		1.8	1.7	
8		0.2	0.1	

[a] These are predicted cross sections for the pure two-quasiparticle states indicated, before any Coriolis mixing has been considered.

[b] These values are predicted cross sections for the states after Coriolis mixing of the wave functions has been included, as described in the text.

[c] These are experimental cross sections, from Table I, to which the predicted values can be compared.

value, it would be expected that the total cross section for $7/2^+[404]$ proton pickup would also be ~90 μb/sr, and that half of this amount should appear in each of the $K^\pi=1^+$ and $K^\pi=8^+$bands. The observed cross sections in Table I agree nicely with this expectation.

D. $K^\pi = 9^-$ $\{9/2^+[624]_\nu + 9/2^-[514]_\pi\}$ configuration

The $9/2^-[514]$ proton orbital is above the Fermi surface in most of the lutetium nuclei, but its excitation energy decreases as the neutron number increases [10,19,20], and it becomes the ground state of ^{181}Lu. Between ^{177}Lu and ^{179}Lu its energy decreases from 150 keV to 35 keV, so in ^{178}Lu it may be expected at about 100 ± 50 keV above the ground state. As mentioned in the previous subsection, the only peaks in the $^{179}\mathrm{Hf}(t,\alpha)$ spectrum, which can be reasonably assigned to the expected l=5 transitions to the 9^- and 10^- members of the band, are at ~120 keV and ~334 keV. The observed cross sections are seen from Table II to be ~50% larger than predicted, but it is also known that a similar difference appeared for the $9/2^-[514]$ strengths to the odd-mass ^{177,179}Lu nuclides [10]. It is possible that some unusual pairing effects are taking place for this orbital above the Fermi surface, making it difficult to estimate the fullness factor, V^2, reliably for the predicted cross sections. If one notes that the observed cross sections [10] at θ=25° for the 11/2 $9/2^-[514]$ levels are 130 μb/sr in ^{177}Lu and 150 μb/sr in ^{179}Lu, a reasonable estimate for the transfer cross section to ^{178}Lu could be the average of these, or ~140 μb/sr. Of this, ~70 μb/sr would be found in each of the K^π=0^- and K^π=9^- bands formed by transfer of the $9/2^-[514]$ proton. Viewed in this way, the total observed cross section of 66 μb/sr to the 9^- and 10^- levels of the K^π=9^- band in Table I seems quite reasonable.

The antiparallel coupling of these two nucleons forms a K^π=0^- band in which the total strength is distributed over many levels and therefore no strong peaks are expected. There are weak transitions listed in Table I which remain unassigned and are likely candidates for members of this band, as discussed in Sec. III F below. However, the present experiment by itself does not provide sufficient basis for reliable assignments.

E. The $K^\pi = 4^+$ and $K^\pi = 5^+$, $\{9/2^+[624]_\nu \pm 1/2 + [411]_\pi\}$ configurations

The largest peaks in the $^{179}\mathrm{Hf}(t,\alpha)$ spectrum are predicted to result from pickup of a $1/2^+[411]$ proton. This is consistent with the (t,α) studies [10] of ^{177,179}Lu, in which the $1/2^+[411]$ bands had the largest cross sections in the spectra. Furthermore, these strong transitions are dominated by l=2 transfers. In the ^{179}Hf(t,α) spectrum of Fig. 1 there is a series of large peaks starting with the one for the 656 keV level that have angular distributions indicating dominant l=2 transfers. The Gallagher-Moszkowski splitting should cause the K=4 band to have the lowest energy, and this leads to the band assignments shown in Fig. 1 and Table I. Upon comparing the relative intensities within the bands with predicted values, it is seen from Table II that, before the effects of Coriolis mixing are considered, the I,K^π=$5,4^+$ strength is calculated to be only ~60% of that for the $4,4^+$ bandhead. Experimentally, these two intensities are quite similar. This is explained by the Coriolis-mixing calculations, in which some strength from the $5,5^+$ bandhead is transferred down to the $5,4^+$ level.

It is noted that the total absolute cross section for these bands is larger than the predicted value, which is reminiscent of the situation in the $^{178,180}\mathrm{Hf}(t,\alpha)$ studies [10] where the observed $1/2^+[411]$ transfer strengths were similarly greater than predicted.

F. Other levels

The $5/2^+[402]$ proton orbital lies above the Fermi surface, but has been observed [10] with appreciable (t,α) cross section at 458 keV excitation in ^{177}Lu and at 653 keV in ^{179}Lu. Thus, it can be expected near ~1/2 MeV in ^{178}Lu. The K^π=7^+ parallel coupling $9/2^+[624]_\nu$+$5/2^+[402]_\pi$ should have the lowest energy, and the I=7 bandhead should be the only strongly populated band member, since the $5/2^+[402]$ wave function is predominantly $d_{5/2}$. The cross section for this peak is predicted to be 20–30 μb/sr, depending on the pairing fullness factor, V^2, used in the calculation. The only unassigned peak near 1/2 MeV excitation, which has an intensity comparable to this, is for the ~499 keV level. This peak has 33 μb/sr at θ=25°, of which about half is due to a $^{178}\mathrm{Hf}(t,\alpha)^{177}$Lu impurity line. In Table I this level is tentatively suggested as a possible I,K^π=$7,7^+$ $\{9/2^+[624]_\nu + 5/2^+[402]_\pi\}$ configuration but there is not enough evidence for a firm assignment. The K^π=2^+ band from antiparallel coupling for this configuration, expected at ~650 keV, would be obscured by the strong peak at 656 keV for the K^π=4^+ band, discussed in the preceding subsection.

There is also a peak for the 215 keV level which has 26 μb/sr, of which ~1/3 is due to a $^{178}\mathrm{Hf}(t,\alpha)^{177}$Lu impurity line. Other unassigned but weakly populated levels below 900 keV are found at 366 keV and ~475 keV. It is probable that some of these are members of the K^π=0^- $\{9/2^+[624]_\nu - 9/2^-[514]_\pi\}$ band which is expected but was not located.

Above 1 MeV excitation there are several fairly strongly populated states (e.g., at 1068 keV, 1133 keV, 1167 keV, etc.) for which the angular distributions suggest that the transfer is dominated by l=2. It is most likely that these are due to pickup of a $3/2^+[411]$ proton, as previous (t,α) studies [10] showed strong l = 2 transitions for the $5/2,3/2^+[411]$ levels at 1133 keV in ^{177}Lu and 1189 keV in ^{179}Lu. The Gallagher-Moszkowski rule would place the K^π=6^+ $\{9/2^+[624]_\nu + 3/2^+[411]_\pi\}$ band lowest, and its spin 6 and 7 members should be populated by strong l=2 transitions. However, no specific assignments are being presently suggested for these levels.

IV. DISCUSSION

Figure 3 shows all the known ^{178}Lu energy levels up to 1.2 MeV, including results from the present ^{179}Hf(t,α) experiment and also the earlier beta-decay [4-7] and ^{176}Lu(t,p) reaction [8] studies. Two specific features of this scheme are discussed here. Firstly, the energy placement of all the expected low-lying high-spin levels is examined, in order to seek an unambiguous description of the 23 min isomer. Next are considered the expected low-lying ($E_x \leq 500$ keV) low-spin ($I \leq 2$) levels that are likely to be populated in the ^{178}Yb beta decay, some of which may also appear in the present study. Estimated excitation energies for the 2qp bandheads and associated rotational levels are obtained either from the experimental spectra [1,2] of ^{176}Lu and ^{180}Ta or from theoretical calculations using the modeling formulation of Sood and collaborators [21–24].

A. Energies of high-spin levels and character of the 23 min isomer

Considering the available single-particle orbitals [19] around the $(Z,N) = (71,107)$ Fermi surface, the spin-parity configurations of low-lying ($E_x \leq 300$ keV) high-spin ($I \geq 6$) levels expected in the ^{178}Lu spectrum are $8^+\{9/2^+[624]_\nu + 7/2^+[404]_\pi\}$, $9^-\{9/2^+[624]_\nu + 9/2^-[514]_\pi\}$, and $7^-\{7/2^-[514]_\nu + 7/2^+[404]_\pi\}$. The next set of high-spin levels, including $7^+\{9/2^+[624]_\nu + 5/2^+[402]_\pi\}$ and $8^+\{7/2^-[514]_\nu + 9/2^-[514]_\pi\}$, are expected at $E_x \geq 500$ keV. With an $I^\pi=1^+$ ground state, the lowest of the 8^+, 9^-, 7^- bandheads should occur as a long-lived beta-decaying ^{178}Lu isomer. The latest Nuclear Data Sheets [3] lists $E(7^-) = 120 \pm 5$ keV and $E(9^-) = 220 \pm 45$ keV. Furthermore, the observed [1] energy separation of the (1^+, 8^+) ground-state GM pair in the isotonic neighbor ^{180}Ta suggests $E(8^+) \simeq 180$ keV in ^{178}Lu, and in the present work the 8^+ level has been assigned at 187 keV. Since a 220 keV 9^- state could undergo relatively much faster $E1$ and $E2$ transitions, respectively, to the lower-lying 8^+ and 7^- levels in ^{178}Lu itself, its identification with the observed 23 min beta-decaying isomer would seem unreasonable. The alternate assumption of the 120 keV 7^- level as the isomer, adopted by Wapstra *et al.* [25], is inconsistent with the observed [6,7] features of its beta decays to high-spin levels in ^{178}Hf (in particular, the beta transition to a level with $I^\pi=9^-$). This long-standing ambiguity is now examined in the light of assignments from the present work.

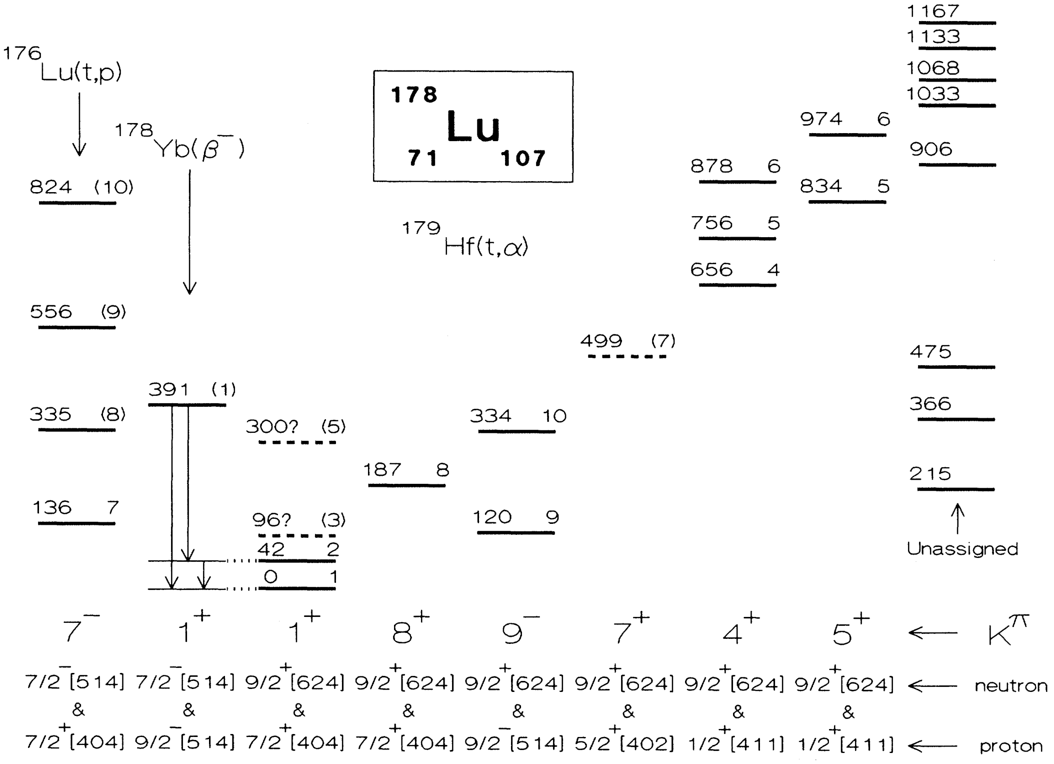

FIG. 3. Level scheme for ^{178}Lu below 1170 keV. The numbers shown on each level are excitation energies in keV (on the left) and spin I (on the right) with level parity defined by the band quantum number K^π shown below each column. Tentative level assignments are shown by dashed lines with spins in parentheses, and tentative energies are indicated by a question mark next to the energy value. The bottom two rows list the Nilsson model asymptotic quantum numbers $\Omega^\pi[Nn_3\Lambda]$ for the neutron (upper rows) and the proton (lower row) for each 2qp band. The first column on the left shows the $K^\pi=7^-$ band levels (with revised energies, as discussed in the text) populated in the ^{176}Lu(t,p) reaction [8]. The next column shows levels populated in the ^{178}Yb beta decay [5]. All other entries are from ^{179}Hf(t,α) reaction data of the present study, with unassigned levels shown in the last column on the right.

Girschick *et al.* [8] reported $Q(t,p) = 4482 \pm 5$ keV for the first state populated in their ^{176}Lu(t,p) reaction. Considering that this reaction selectively populates states with the same 2qp structure as the target ground state, this lowest observed state was assigned $K^{\pi} = 7^{-}$ $\{7/2^{-}[514]_{\nu} + 7/2^{+}[404]_{\pi}\}$ similar to the ^{176}Lu ground state. Using a (t,p) Q value derived from 1977 mass tables for the unobserved ground state, they [8] quoted $E_x(7^{-}) = 98 \pm 5$ keV with an additional inherent uncertainty of ± 40 keV from the ^{178}Lu mass value. The 1983 mass tables [25] revised the adjusted ^{178}Lu mass excess to be $-50\,336 \pm 25$ keV, yielding [3] an excitation energy of 120 ± 25 keV for the 7^{-} level. The more precise ^{178}Lu mass excess $-50\,351 \pm 5$ keV derived in the present study accordingly corresponds to $E_x(7^{-}) = 136 \pm 7$ keV.

The excitation energy previously adopted [3] for the level, $E_x(9^{-}) = 220 \pm 45$ keV, was arrived at by using $Q(\beta^{-})$ values of 2028 ± 33 keV and 2248 ± 30 keV, respectively, for the 28 min ground state and the 23 min isomer decays. The former value adopted by the Nuclear Data Sheets evaluator [3] differs significantly from its adjusted value (2112 ± 25 keV) quoted by Wapstra *et al.* [25]. Using the present more precise ^{178}Lu mass with the ^{178}Hf mass value from 1986 mass tables [12], one gets

$$Q(\beta^{-}; \text{g.s.}) = \Delta M(^{178}\text{Lu-}^{178}\text{Hf}) = 2095 \pm 5 \text{ keV}.$$

Taken together with the above-quoted $Q(\beta^{-}$;23 min), this result places the isomer energy at 153 ± 30 keV, which is in reasonable agreement with $E_x(9^{-}) = 120 \pm 3$ keV determined directly in the present ^{179}Hf(t,α) study. This experiment has also determined $E_x(8^{+}) = 187 \pm 1$ keV. These considerations unambiguously place the $K^{\pi}=9^{-}$ bandhead as the lowest high-spin level, lower in energy than both the $K^{\pi}=7^{-}$ and $K^{\pi}=8^{+}$ bandheads, thus confirming its identification with the 23 min isomer and resolving the previously existing conflicts. These results on the relative ordering of the low-lying high-spin bands are in agreement with model calculations [23,24] for the bandhead energies of these 2qp configurations.

B. Low-lying low-spin levels

Levels with $I^{\pi} = 0^{\pm}$, $1^{\pm}$, and 2^{-} in ^{178}Lu are expected to be populated in allowed or first-forbidden beta decays from the $I^{\pi}=0^{+}$ ^{178}Yb ground state. Consideration of the available configuration space [19] shows that, in addition to the ground state $K^{\pi}=1^{+}$ band, the only $K \leq 2$ bands expected below 600 keV in ^{178}Lu have spin-parity configurations $0_1^{-}\{9/2^{+}[624]_{\nu} - 9/2^{-}[514]_{\pi}\}$, $0_2^{-}\{7/2^{-}[514]_{\nu} - 7/2^{+}[404]_{\pi}\}$, and $1_2^{+}\{7/2^{-}[514]_{\nu} - 9/2^{-}[514]_{\pi}\}$. This ^{178}Yb beta decay ($Q_{\beta} \simeq 640$ keV) is expected to populate levels with $I^{\pi}=0^{-}$, 1^{-}, 2^{-} in both the negative parity bands, and both the $K^{\pi}=1^{+}$ bandheads. However, the earlier ^{178}Yb beta-decay study [5] had identified only one beta branch to the 391 keV level, leaving even the beta feeding to the 1^{+} ground state undetermined. Assuming the limiting value of $\log ft \simeq 4.3$ for this branch from systematics for the deformed region, Orth *et al.* [5] deduced $\leq 10\%$ of the β intensity populated this level. Our calculations suggest that even a 2% β intensity into the 391 keV level would still correspond to $\log ft \leq 5.2$ for this decay, permitting its classification as allowed unhindered [9], consistent with the 2qp configuration shown in Fig. 3. These calculations also reveal that a β intensity of $\geq 50\%$ to the ground state, corresponding to $\log ft \leq 5.2$, would indicate considerable $\Delta K=0$ configuration mixing between the two 1^{+} bands. The existence of such a mixing is supported by the observed gamma transition connecting the two bands, since a direct transition, involving simultaneous change of both the neutron and proton orbitals, would not be allowed between pure 2qp states. These calculations also suggest the presence of other undetected beta branches. Analogy with the observed [2] (7^{-},0^{-}) GM doublet bands in ^{176}Lu suggests the ^{178}Lu 0_2^{-} band levels with I^{π}, E_x(keV) as follows, 1^{-}, $\sim$260 keV; 0^{-}, $\sim$375 keV; and 2^{-}, $\sim$440 keV. These levels are not observed in the (t,α) reaction, but should be populated in ^{178}Yb decay. For the 0_1^{-} band levels, our calculation of the Newby odd-even shift using the Sood-Ray formulation [26] and Elmore-Alford sign convention [27] yields $E_N \simeq -25$ keV. Model calculations [21–24] then suggest the following rotational energies, estimated to be within ± 25 keV, for this band: 0^{-}, $\sim$150 keV; 1^{-} and 2^{-}, $\sim$210 keV; 3^{-}, $\sim$310 keV; 4^{-}, $\sim$360 keV; 5^{-}, $\sim$470 keV. The present ^{179}Hf(t,α) experiments have unassigned peaks (see Table I and Fig. 3) at 215 keV, 366 keV, and 475 keV which could be possible candidates for these 0_1^{-} band levels. It would be of interest to reinvestigate the ^{178}Yb beta decay carefully to identify beta branches to the ^{178}Lu ground state and the other low-spin negative parity states predicted below 500 keV. Identification of a level at $\sim$215 keV having $I^{\pi} \leq 2^{-}$ could provide interpretations for some of the unassigned levels populated in the present experiment.

V. SUMMARY

The (t,α) single-proton-pickup reaction has been used to study levels in the neutron-rich odd-odd nucleus ^{178}Lu. Assignments have been made for two-quasiparticle configurations involving the unpaired $9/2^{+}[624]$ target neutron coupled with the $7/2^{+}[404]$, $9/2^{-}[514]$, and $1/2^{+}[411]$ protons. A more precise value for the ^{178}Lu mass has been obtained from experimental (t,α) Q values. This, combined with the band assignments from the present work, permits a consistent explanation for the previously conflicting interpretations concerning the 23 min beta-decaying ^{178}Lu isomer. The $K^{\pi} = 9^{-}$ $\{9/2^{+}[624]_{\nu} + 9/2^{-}[514]_{\pi}\}$ bandhead has been placed at 120 keV and forms the lowest-lying high-spin state, consistent with indications from β-decay studies that the isomer had $I^{\pi}=9^{-}$. This excitation energy is significantly less than the previously adopted value of 220 ± 45 keV based on $Q(\beta)$ differences that are now shown to be inconsistent with recent mass values. The $K^{\pi}=7^{-}$ $\{7/2^{+}[404]_{\pi} + 7/2^{-}[514]_{\nu}\}$ level, previously known from (t,p) measurements and located at 120 ± 25 keV above the unobserved ground state, is now shifted to an excitation energy of 136 ± 7 keV due to the new value for the ^{178}Lu mass. Thus the 9^{-} level is now clearly placed below the 7^{-} one, thereby producing the 9^{-} isomer.

Some weakly populated levels at excitation energies below 0.5 MeV remain unassigned and are likely associated with low-K bands, such as the $K^{\pi}=0^{-}$ $\{9/2^{+}[624]_{\nu} - 9/2^{-}[514]_{\pi}\}$ configuration. It would be useful to perform a very careful reexamination of the beta decay of ^{178}Yb to study the feeding of low-spin states in ^{178}Lu.

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