Title
ENERGY LEVELS OF 71Lu172101

Authors
Valentin, J.
Horen, D.J.
Hollander, J.M.

Publication Date
1961-07-01

UCRL -9780

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Radiation Laboratory

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ABSTRACT

The energy levels of the odd-odd nucleus Lu^{172} populated from the electron-capture of Hf^{172} have been examined with high-resolution 180° spectrographs, a double-focusing spectrometer, and with scintillation techniques. A new M3-isomer in Lu^{172} has been found, with half-life 3.7 ± 0.5 minutes and energy 41.6 kev. Several alternative level schemes for Lu^{172} are presented and discussed in terms of expected configurations of the 71st proton and 101st neutron.

ENERGY LEVELS OF $_{71}Lu^{172}_{101}$ †

J. Valentin,[x] D. J. Horen, and J. M. Hollander

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I. INTRODUCTION

From studies of the energy levels of odd-odd nuclei it is possible to gain information about neutron-proton forces in nuclei. Discussions and analyses of the coupling rules appropriate for odd-odd deformed nuclei have been given by Gallagher and Moszkowski,[1] and more recently, for the lighter nuclei, by Brennan and Bernstein.[2] The desirability of further studies of odd-odd nuclei is, as pointed out by these and other authors, obviously great. We report here on an examination of the levels of the odd-odd deformed nucleus $_{71}Lu^{172}_{101}$ which are populated from the decay of $_{72}Hf^{172}_{100}$.

Hf^{172} was discovered by Wilkinson and Hicks in 1951[3] and assigned by them as an activity which decays by electron capture with half-life of about 5 years. There has been no work reported subsequently on its decay properties. We have synthesized Hf^{172} by intensive irradiations both of natural ytterbium and of the "separated isotope" $_{70}Yb^{172}$ * with 48 Mev helium ions from the 60-inch Crocker cyclotron. This research was carried out concurrently with studies of the decays of the neighboring odd-mass isotopes Hf^{171} and Hf^{173}.[4]

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† Work done under the auspices of the U. S. Atomic Energy Commission.

x On leave from Laboratoire de Physique Nucleaire - ORSAY - France.

* The separated isotopes were purchased from the Stable Isotopes Division, Oak Ridge National Laboratory.

II. EXPERIMENTAL EQUIPMENT

The internal conversion spectrum of Hf^{172} was examined with 180° photographic recording permanent-field spectrographs of field strengths 50, 100, 150, 215, and 340 gauss and also with a 50-gauss spectrograph employing a 10.8 kV "pre-acceleration" voltage applied to the source.[5] A 25-cm double-focusing spectrometer was used to measure the intensities of some of the conversion lines. Gamma spectra were taken with 2.5 x 0.3, 5.1 x 5.1, and 7.6 x 7.6 cm. NaI(Tl) crystals coupled to 100-channel Penco or 256-channel T.M.C. analyzers, and gamma-gamma coincidence experiments were done with conventional "fast-slow" apparatus with resolving time $2\tau = 6 \times 10^{-8}$ seconds.

III. SOURCE PREPARATION

The Hf^{172} sources were the same as those used for a study of 24.0-hour Hf^{173} decay, already reported by us.[4] The chemical procedure, involving anionic adsorption-elution from HCl solutions has been described by Tocher and Hollander.[6] Because the chemistry was always performed immediately after the end of irradiation, the sources contained both Hf^{172} and Hf^{173} and therefore, subsequently, also the daughter activities 6.7-day Lu^{172} and 1.6-year Lu^{173}.

IV. PHOTON SPECTRUM

The scintillatron spectrum of a sample of Hf^{172}, containing a small amount of 70-day Hf^{175}, was taken with a 2.5 cm x 0.3 cm NaI(Tl) crystal covered with thin beryllium; this spectrum is shown in Fig. 1. The fraction of the peak at 24-kev attributable to a 24-kev photon was determined by an absorption experiment described in Section VI. The measured relative photon intensities are given in Table III.

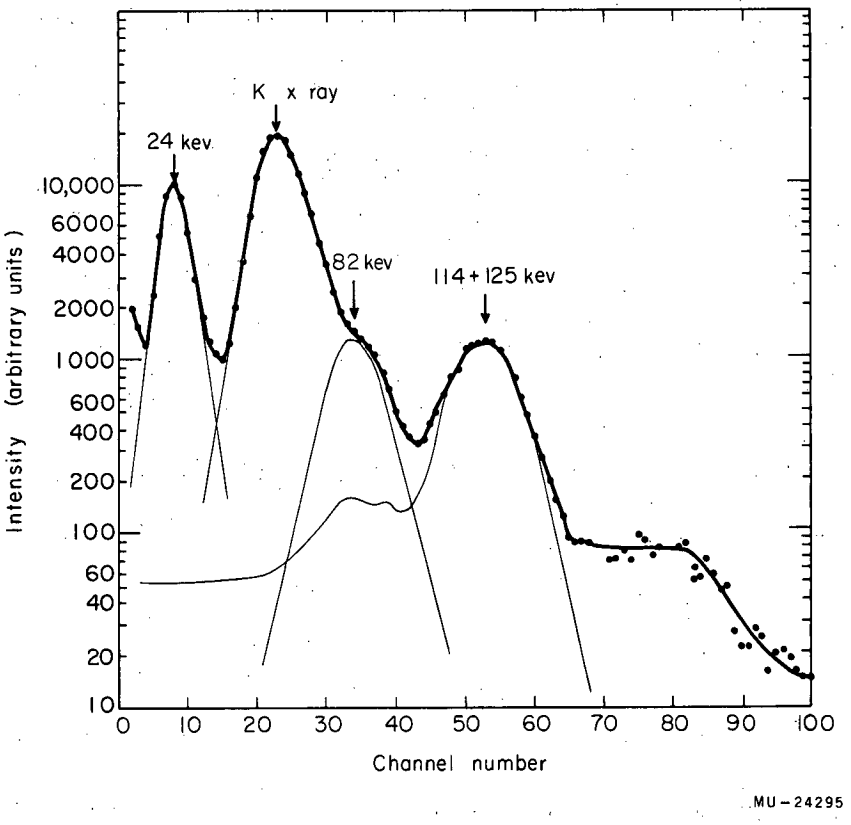

Fig. 1. Photon spectrum of Hf^{172}. The counts above channel 70 are due to Compton-scattered photons from the strong 343-kev gamma ray in Hf^{175}, present in small amounts in the source.

V. INTERNAL CONVERSION SPECTRUM

The 180° spectrograph plates, exposed for periods of up to six weeks, contained also the spectra of Lu^{172} and Lu^{173}. These latter spectra have been studied extensively by Harmatz, Handley, and Mihelich,[7] and as our own observations confirmed their findings it was not a difficult matter to distinguish the conversion lines of Hf^{172} from those of the two lutetium activities.

Table I presents our Hf^{172} internal conversion energy and intensity data. The intensities of some of the strongest lines were also determined with the double-focusing spectrometer, and these results are also given in Table I. Because of extensive calibrations of the instruments, we estimate the absolute accuracy of the energy measurements to be ± 0.1%. The relative intensities of close-lying lines are probably good to ± 20%, but errors exceeding 50% may be expected in the relative intensities of lines lower in energy than ~ 30 kev.

VI. TRANSITION MULTIPOLARITIES

The Hf^{172} spectrum, a fairly simple one, contains only seven transitions, all with energies under 130 kev. At these low energies, L-conversion subshell ratios are known to depend sensitively on multipole order, so an analysis of the relative subshell intensity data allows in most cases the unambiguous determination of transition multipole orders. The transitions are discussed below and the multipolarity assignments are summarized in Table II.

Table I. Hf^{172} Internal Conversion Data

Electron Energy (kev)	Conversion Shell	Transition Energy (kev)	Selected Transition Energy (kev)	Intensity[a] 180° spect.	Intensity[a] Double Focusing Spectrometer[b]	Comments
13.13	L_I	24.00		~ 600		
13.63	L_{II}	23.98		~ 440		
14.74	L_{III}	23.98		780		
21.52	M_I	24.01		130		
21.74	M_{II}	24.00		90		
21.96	M_{III}	23.98		160		
23.59	N	~24.00		80		
			23.99			
31.00	L_I	41.88		530		
31.49	L_{II}	41.84		65		
32.63	L_{III}	41.88		1,250		
39.35	M_I	41.85		~ 125	620	mixed with K 100.7 Lu^{173}
39.82	M_{III}	41.84		375		
41.35	N_I	41.85		40		
41.48	N_{III}	41.84		125		
41.81	O	41.86				mixed with M_{II} 44.1
			41.86			
-----	L_I	-----		-----		L_I not seen; upper limit 40
33.74	L_{II}	44.08		500		
34.83	L_{III}	44.08		560		
41.81	M_{II}	44.09			380	mixed with O 41.8
42.08	M_{III}	44.11		130		
43.59	N_{II}	44.06		60		
43.72	N_{III}	44.08				
			44.08			

Table I (Con't.)

Electron Energy (kev)	Conversion Shell	Transition Energy (kev)	Selected Transition Energy (kev)	Intensity[a] 180° spect.	Intensity[a] Double Focusing Spectrometer[b]	Comments
59.16	L_I (?)	70.03		70		
59.65	L_{II}(?)	70.04		56		
18.46	K	81.78		1,050		
70.92	L_I	81.80		150	124	
71.45	L_{II}	81.80		20		
-----	L_{III}	-----		-----		L_{III} not seen; upper limit 10
79.29	M_I	81.78	81.8	40		
50.76	K	114.07		170		
103.19	L_I	114.06		25		
103.73	L_{II}	114.10				mixed with 112.8 Lu^{172}
111.45	M	113.95	114.0	10		
62.52	K	125.84		600	670	
114.97	L_I	125.84		[100]	[100]	values normalized here
115.47	L_{II}	125.82		15		
-----	L_{III}	-----		-----		L_{III} not seen; upper limit 5
123.29	M	125.80		40		
125.26	N	125.77	125.8	17		

[a] Arbitrary scale.

[b] No corrections have been made for absorption in the 1/4-mil (930 μgm) Mylar counter window.

Table II. Hf^{172} Transition Multipolarity Assignments

Transition Energy (kev)	Subshell Ratios (Experimental)	Subshell Ratios (Theoretical[a])	Multipole Order
24.0	$L_I/L_{II}/L_{III}$= 1.0/0.7/1.3 $M_I/M_{II}/M_{III}$= 1.0/0.7/1.2	E1: $L_I/L_{II}/L_{III}$= 1.0/0.88/1.3 M1-3% E2: $L_I/L_{II}/L_{III}$= 1.0/0.88/1.1	E1[b]
41.8	$L_I/L_{II}/L_{III}$= 1.0/0.12/2.4	M2: $L_I/L_{II}/L_{III}$= 1.0/0.07/0.39 M3: $L_I/L_{II}/L_{III}$= 1.0/0.10/1.9 M4: $L_I/L_{II}/L_{III}$= 1.0/0.12/9.2	M3
44.1	$L_I/L_{II}/L_{III}$= .../1.0/1.1	E2: $L_I/L_{II}/L_{III}$= 0.01/1.0/1.1	E2 (M1-E2)
81.8	$L_I/L_{II}/L_{III}$= 1.0/0.13/...	M1: $L_I/L_{II}/L_{III}$= 1.0/0.09/0.012 M2: $L_I/L_{II}/L_{III}$= 1.0/0.11/0.24 E1: $L_I/L_{II}/L_{III}$= 1.0/0.34/0.40	M1
114.0	K/L_I= 6.8	M1: K/L_I= 5.1 M2: K/L_I= 4.1 E1: K/L_I= 6.7	E1,M1
125.8	$L_I/L_{II}/L_{III}$= 1.0/0.15/...	M1: $L_I/L_{II}/L_{III}$=1.0/0.09/0.01 M2: $L_I/L_{II}/L_{III}$= 1.0/0.12/0.12 E1: $L_I/L_{II}/L_{III}$= 1.0/0.21/0.23	M1

[a] Reference 8.
[b] See text.

24.0-kev Transition

It is easy to distinguish a low-energy E1 transition from any other pure multipole by its L- or M-subshell conversion pattern, and it is this E1 pattern we see in the case of the 24.0-kev transition. A quite similar pattern would unfortunately also be given by an M1 transition with 3±0.5% E2 admixture (see Table II), though the probability of having just this particular admixture is remote. However, the two situations can be distinguished by a measurement of the absolute L-conversion coefficients since the (theoretical) values involved are:

$$\frac{e}{\gamma}\,(E1) = 2.1; \quad \frac{e}{\gamma}\,(97\%\ M1,\ 3\%\ E2) = 72.9.^{8}$$

By a simple experiment in which the photon spectrum was examined with thin Pb absorbers interposed between source and crystal, the 24-kev photon was distinguished from the 23-kev "escape peak" from the Lu K X-rays, and the measured photon abundance was found to be within 10% of the value calculated from the experimental electron intensity and the theoretical E1 conversion coefficient (see Table III). This established unambiguously that the 24-kev radiation is electric dipole.

41.8-kev Transition; a new M3 Isomer in Lu^{172}

By its L-subshell pattern the 41.8-kev transition appears clearly to be an M3. Because the theoretical, single-proton, estimate for the half-life of a 41.8-kev M3 transition is ~10 seconds and M3 transitions have hindrance factors ranging from 1-100, it seemed feasible to attempt a rapid chemical separation of this isomer.[9] Examination of the photon spectrum of the isomer would also help to define its position in the level scheme.

Table III. Hf^{172} Transition Intensities

Transition Energy (kev)	Total Electron Intensity	Photon Intensity[a]		Total Relative Transition Intensity[c]
		Calculated	Experimental	
24.0	2280	700	600	3000
41.8	2410	~ 0.1	---	2400
44.1	1250	~11	---	1250
70.0 (?)	----	---	---	----
81.8	1210	200	265	1400
114.0	195	80	[580][b]	~300
125.8	770	500		1300
K X-rays	----	3700	3760	3700

[a] Same scale as Table I.

[b] Experimental and calculated values normalized here.

[c] The experimental error of the relative transition intensities is estimated to be ± 20%.

Accordingly, a carrier-free source of Hf^{172} - Lu^{172} was adsorbed onto a small anion exchange column from concentrated HCl solution saturated with HCl gas. Following extensive washing with 12-M HCl to remove 6.7 day Lu^{172} from the column, rapid elutions with 12M HCl were made after growth intervals of 30-seconds, 1 minute, etc. The activity was transferred within a few seconds to the 2.5 x 0.3 cm NaI(Tl) crystal detector and, with the single-channel analyzer set to accept pulses corresponding to Lu L X-rays, a decay period of 3.7 ± 0.5 minutes was readily observed. One of the decay curves is shown in Fig. 2. The experiment was repeated several times.

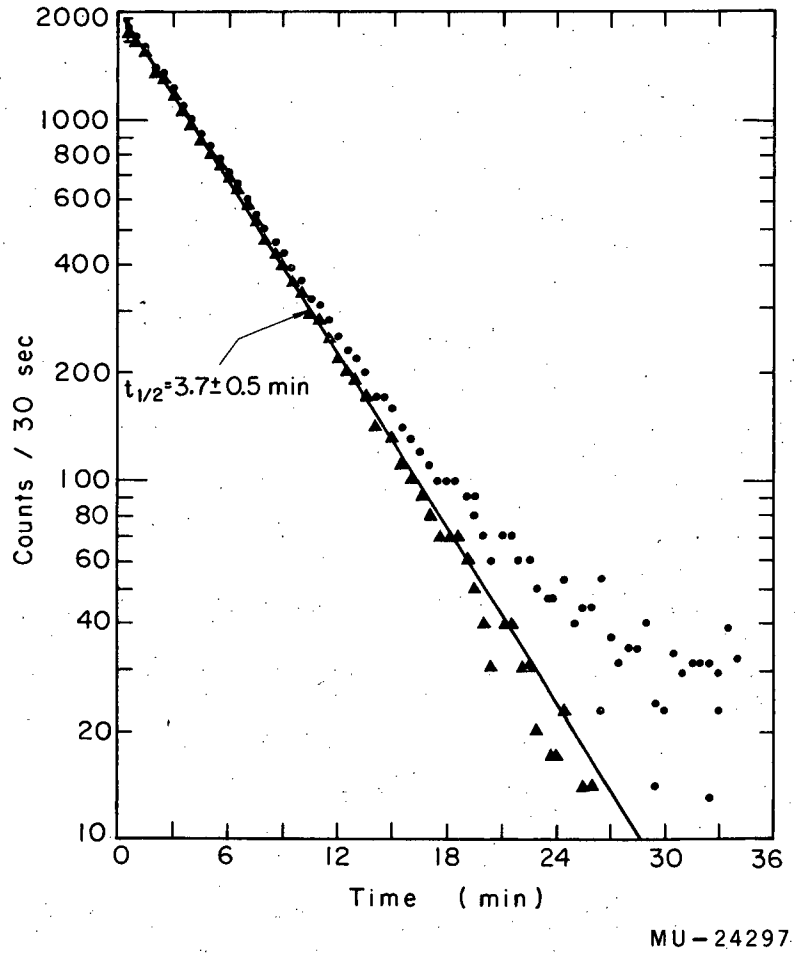

Fig. 2. Decay curve of L X-rays from Lu^{172m}.

From the measured half-life we calculate that the hindrance factor of the M3 radiation is ~ 22 (if the conversion coefficient is not anomalous), which is within the range of hindrance factors previously observed for M3 transitions. According to the asymptotic selection rules appropriate for electromagnetic transitions in deformed nuclei[10,11] and to the state assignments discussed below, this transition is classified as "hindered".

Examination of the photon spectrum of the 3.7-minute Lu^{172m} revealed only L X-rays, which strongly indicates that the isomeric transition lies at the bottom of the level scheme.

The 44.1-, 81.8-, and 125.8-kev Transitions

The energy difference between the 125.8- and 81.8-kev transitions, 44.04 ± 0.15 kev, agrees within 0.1% with the measured transition energy 44.08 ± 0.05 kev, establishing clearly the cascade-crossover relationship of these transitions. That they lie above the isomer was also verified by observing prompt coincidences between the 125.8-kev transition and K X-rays.

It is known from the L-subshell patterns that the 81.8- and 125.8-kev transitions are M1 and that the 44.1-kev transition is an E2, though strictly speaking a small amount of M1 admixture in the 44.1 cannot be ruled out.

VII. INTERPRETATION OF LEVEL SCHEME

Some of the pertinent experimental facts about the Hf^{172} decay scheme are:

(1) The 41.8-kev M3 isomer lies at the bottom of the scheme.

(2) The intensities of the 41.8-kev, 24.0-kev, and 81.8-kev plus -125.8 kev transitions appear to be equal, within experimental error, indicating that the 41.8-, 24.0-, and 125.8-kev transitions form a cascade, with the 81.8- and 44.1-kev transitions parallel with the 125.8.

(3) We do not know the order of the 24.0-125.8 pair nor that of the 81.8-44.1 pair. We have searched for but have been unable to find additional crossover transitions which could provide this information.

We cannot therefore establish, from experimental data alone, a unique level scheme. It is possible, however, with use of information about single particle states in neighboring nuclei plus general beta-decay selection rules to select from the possible schemes those that appear most probable.

Let us discuss the low-lying states expected in $_{71}Lu^{172}_{101}$. The ground state of the 71^{st} proton has in all known cases been reported in the Nilsson designation[4,11] to be 7/2+ [404]. The ground state of the 101^{st} neutron is 1/2- [521].[4,12] It is reasonable to assume then that the ground state of the odd-odd nucleus Lu^{172} is composed of these two configurations. According to the Gallagher-Moszkowski coupling rules,[1] the proton and neutron would here combine to form the doublet 4- and 3-, with the higher spin state lying lower. From a study of the electron-capture decay of the 6.7-day Lu^{172} ground state, Harmatz et al.[7] have concluded that the spin must be 4 or 5, so we shall select the assignment 4- for Lu^{172}.

In the subsequent discussion we keep in mind the fact that the parent isotope $_{72}Hf^{172}$, being even-even, can be considered to have spin zero and even parity. Therefore the states in Lu^{172} receiving electron-capture population must have spins no greater than 2 if the parity is odd or no greater than 1 if the parity is even.

What states are expected as excited levels in Lu^{172}? In Lu^{173}, the first excited proton configuration observed is 1/2- [541],[4] and the 9/2- [514] state may also be near-lying.[11] 7/2+ [633] is the ground state of the $99^{\underline{th}}$ neutron and 5/2- [512] is the ground state of the $103^{\underline{rd}}$ neutron,[11] so it is likely that these orbitals occur also as low-lying excited states of the $101^{\underline{st}}$ neutron.

Table IV summarizes the spins and parities obtainable from combinations of the above p- and n- orbitals, with the predicted lower-lying spin written first. It is interesting that all the observed transitions in Lu^{172} can be accounted for by use of only the first three states given in Table IV, those containing the proton orbital 7/2+ [404] and ground state orbitals of the $101^{\underline{st}}$, $103^{\underline{rd}}$, and $99^{\underline{th}}$ neutrons.

Harmatz et al.[12] have found that the ground state of $_{71}Lu^{174}_{103}$ has spin and parity 1-. Although these workers give no Nilsson assignment for this state, it most likely is the (p) 7/2+ [404], (n) 5/2- [512] configuration, which produces the 1- and 6- intrinsic states observed by them.

In the case of Lu^{172}, the 41.8-kev M3 transition decays directly to the ground state (which we have assigned as 4-) so the spin and parity of the isomeric level is therefore 1-. This low-lying excited state is in all likelihood the same 1- configuration observed by Harmatz et al.[12] as the ground state of Lu^{174}.

Table IV. Expected States in Lu^{172}.

Proton Orbital	Neutron Orbital	$I\pi(p+n)$
7/2+ [404]	1/2- [521]	4- , 3-
	5/2- [512]	1- , 6-
	7/2+ [633]	0+ , 7+
1/2- [541]	1/2- [521]	1+ , 0+
	5/2- [512]	2+ , 3+
	7/2+ [633]	3- , 4-
9/2- [514]	1/2- [521]	4+ , 5+
	5/2- [512]	7+ , 2+
	7/2+ [633]	8- , 1-

Beyond this point our analysis must be partly speculative. Fig.3 shows four alternative possibilities for the Lu^{172} level assignments, consistent with population from the decay of the even-even nucleus Hf^{172} and with the expected states given in Table IV. Scheme (a) does not seem likely. The 0+ state, assigned as the upper member of the K = 1+, K = 0+ doublet formed from the 1/2- [541] proton state and 1/2- [521] neutron state, would be expected to decay to the 2+ rotational state of the K = 1+ band, and we see no evidence for either this transition or this state. With this assignment, the E1 transition would also be expected to be a highly hindered, two-particle transition. Experimentally we know this state has a half-life less than 4×10^{-8} seconds. (A time-to-height converter was used in this measurement, with two NaI(Tl) crystals.)

Scheme (b) is plausible. The assignment of the 3+ state at 147.7 kev as a rotational state of the K=2 band is possible, although the moment of inertia appears too small. That is, in this case the inertial parameter $\hbar^2/\Im$ would be 81.8 kev, compared with 84.2 kev and 78.7 kev for the neighboring even-even nuclei Yb^{170} and Yb^{172}, respectively, whereas one expects a substantially lower value (higher moment of inertia) for the odd-odd nucleus Lu^{172}. The 147.7 kev state could, of course, be the upper member of the K=2+, K=3+ doublet, but in that case we should have to ask why the 3+ rotational state is not seen, at a lower energy.

Scheme (c), with all states intrinsic, is not appealing either, because of the lack of appearance of rotational states based on the intrinsic levels shown.

We favor scheme (d). In this scheme one interprets the 65.9- (0+), 110.0 (2+), and 191.7-kev (1+) levels in terms of a single K=0 rotational band in which the levels of odd spin are displaced relative to those of even spin.

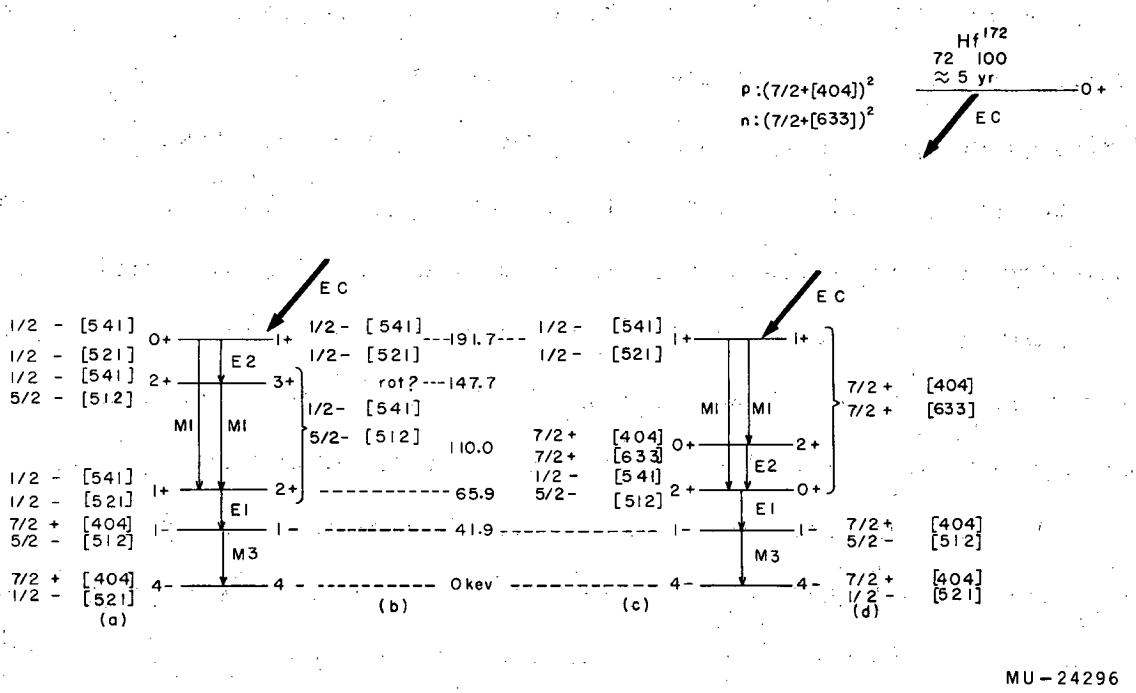

Fig. 3. Alternative level assignments for Lu^{172}.

Newby[13] has discussed the kinds of proton-neutron interaction giving rise to such displacements, which occur only when $K_p = K_n$. In support of this interpretation we note that the experimental reduced photon-transition probability ratio, $\frac{B_{M1}(81.8)}{B_{M1}(125.8)} = 1.8 \pm 0.4$, agrees within the error with the value expected from the branching-ratio rules,[14] 2.0, if all three states have K = 0. If the upper state has K = 1, the branching ratio $\frac{B_{M1}(81.8)}{B_{M1}(125.8)}$ is expected theoretically to be 0.5, in disagreement with the data. On the other hand, if all three states are intrinsic, no simple branching-ratio test can be made.

As a further check on the assignment of the 110.0 level as a 2+ rotational state, we have made an estimate of the inertial parameter $\frac{3\hbar^2}{\mathcal{I}}$ of this band on the basis of that of the even (Yb^{170}) core plus those of the odd proton and odd neutron, in the relevant Nilsson orbitals. For the odd neutron we use the levels of the 7/2+ [633] band of Er^{167} and for the odd proton the 7/2+ [404] band of Lu^{175}. Thus,

$$\left(\frac{3\hbar^2}{\mathcal{I}}\right)_{Lu^{172}} = \frac{3\hbar^2}{\mathcal{I}_{Yb^{170}} + (\mathcal{I}_{Er^{167}} - \mathcal{I}_{Er^{166}}) + (\mathcal{I}_{Lu^{175}} - \mathcal{I}_{Yb^{174}})} = 53.3 \text{ keV}$$

This calculated value is higher than the experimental value, 44.1 keV, by about 20%. Possibly the 0 - 2 spacing of this band is depressed as the result of second-order rotation-particle coupling effects.

A problem with the adopted scheme concerns the primary electron-capture decay probabilities. According to the experimental transition intensity balance, it appears that most of the electron capture decay of Hf^{172} populates the 191.7-kev (1+) state, with little if any population of the 65.9-kev (0+) state. (An upper limit of about 20% can be set on the direct population of the 65.9-kev state.) This difference is difficult to understand, because both final states are interpreted as having the same asymptotic quantum numbers and might be expected to be hindered to about the same degree.

However, the 0+ → 0+ beta decay can take place only via the Fermi interaction, whereas the 0+ → 1+ can also go via the Gamow-Teller interaction, and it is possible that the particular selection rules operating here are more restrictive on the Fermi decay.

A further point can be made about the scheme. A weak M1 (or E1) transition of 114.0 kev is also associated with the decay of Hf^{172}, and possibly also a weak transition of 70.0 kev. The difference between these two energies, 44.0-kev, is very close to the measured energy of the 44.1 kev E2 transition, which suggests the presence of a weakly-populated level in Lu^{172} at either 179.9 kev or 261.7 kev.

ACKNOWLEDGMENTS

We wish to thank Drs. S. G. Nilsson, N. D. Newby, and J. O. Rasmussen for valuable discussions.

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