## Title
NEW TRANSITIONS AND PRECISE ENERGY AND INTENSITY DETERMINATIONS IN THE DECAY OF 177Lum

## Permalink


## Authors
Havenfield, A.J.
Bernthal, F.M.
Hollander, J.M.

## Publication Date
1966-08-01

UCRL-16862

# University of California

# Ernest O. Lawrence Radiation Laboratory

NEW TRANSITIONS AND PRECISE ENERGY AND INTENSITY DETERMINATIONS IN THE DECAY OF $^{177}Lu^m$



Berkeley, California

## DISCLAIMER

To be submitted to Nuclear Physics UCRL-16862

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

# NEW TRANSITIONS AND PRECISE ENERGY AND INTENSITY DETERMINATIONS IN THE DECAY OF $^{177}Lu^m$

A. J. Haverfield, F. M. Bernthal, and J. M. Hollander

August 1966

# NEW TRANSITIONS AND PRECISE ENERGY AND INTENSITY DETERMINATIONS IN THE DECAY OF $^{177}Lu^{m}$ +

A. J. Haverfield, F. M. Bernthal, and J. M. Hollander

Lawrence Radiation Laboratory
University of California
Berkeley, California

August 1966

## Abstract

The decays of $^{177}Lu$ (6.8 day) and $^{177}Lu^{m}$ (155 day) to excited states in $^{177}Hf$ and $^{177}Lu$ have been studied with a high-resolution, lithium-drifted germanium detector. Three new gamma rays have been placed in the decay scheme. Improved relative intensity measurements have allowed recalculation of E2/M1 mixing ratios and E1 branching ratios. Precise determination of the transition energies in $^{177}Lu^{m}$ decay has been made. E1 transition probabilities in $^{177}Hf$ are compared with simple theory.

---

+Work performed under the auspices of the U. S. Atomic Energy Commission.

E

RADIOACTIVITY $^{177}Lu$, $^{177}Lu^{m}$ [from $^{176}Lu$ (n,$\gamma$)] ; measured $E_{\gamma}$, $I_{\gamma}$. $^{177}Hf$ deduced B(E1) and $[(g_K - g_R)/Q_o]^2$. Natural target.

# NEW TRANSITIONS AND PRECISE ENERGY AND INTENSITY DETERMINATIONS IN THE DECAY OF $^{177}Lu^m$

A. J. Haverfield, F. M. Bernthal, and J. M. Hollander

Lawrence Radiation Laboratory
University of California
Berkeley, California

August 1966

## 1. INTRODUCTION

The decay scheme of the 155-day isomer of $^{177}Lu$ offers a sensitive test of present nuclear theory. This isomeric level has been described as arising from a three-quasi-particle configuration involving the 7/2+[404] proton coupled to a 9/2+[624] neutron and a 7/2-[514] neutron. Its spin of 23/2 permits population of high spin members of the low-lying rotational bands in both $^{177}Lu$ and $^{177}Hf$. The numerous cascade-to-crossover branching ratios in these bands provide information on the nuclear g factors and a test of the rotational model. The presence of a number of E1 transitions leading from the K = 9/2+ band to the K = 7/2- band in $^{177}Hf$ is particularly important in view of the present interest in hindered E1 transition rates.

Since the first observation of $^{177}Lu^m$ by Jorgensen et al.[1]), a number of studies have contributed to the elucidation of its decay scheme. Primary among these was the high-resolution study of the gamma-ray spectrum by Alexander et al.[2]) with the Caltech 2-m-radius, bent-crystal spectrometer. Recently two groups[3,4,5]) have added significant data through the use of lithium-drifted germanium (Ge(Li)) gamma-ray detectors. These detectors exhibit the following advantages when compared to the bent-crystal spectrometer: much greater efficiency, better signal-to-noise ratio, and multichannel output of data. With the advent of field-effect-transistor(FET) preamplifiers the resolution of these detectors may now surpass that of the bent-crystal at energies greater than 200 keV. In this paper we will report a study of the gamma-ray spectra of $^{177}Lu$ and $^{177}Lu^m$ with use of a Ge(Li) detector of dimensions 1 $cm^2$ x 5 mm depletion depth that gave a resolution of 1.3 keV at 122 keV. A FET preamplifier of the type described by Elad[6]) is used in conjunction with this detector.

Samples of 7-day $^{177}Lu$ and 155-day $^{177}Lu^m$ were prepared by irradiating natural lutetium metal for periods ranging from 6 days to 41 days with a neutron flux greater than 2.2 x $10^{14}$ in the MTR reactor at Arco, Idaho. After suitable decay periods, the samples were dissolved and lutetium was separated by ion exchange methods from all other activities present. Sources of approximately one millicurie strength were sufficient to allow the acquisition of the spectrum shown in figs. 1-4 in about one day.

## 2. $^{177}Lu$

The energies and relative intensities of the gamma rays found in our gamma-ray spectrum of 7-day $^{177}Lu$ are listed in table 1 along with those of Alexander et al[2]) and Marmier and Boehm[7]). Our intensity data and the known internal conversion coefficients have been used to derive β-decay branching ratios from the ground state of $^{177}Lu$ to the 113.0-, 249.6-, and 321.3-keV levels of $^{177}Hf$. For E1 and M1+E2 transitions we have used the experimental internal conversion coefficients listed in the Nuclear Data Sheets[8]), while for pure E2 transitions we have used the theoretical values of Sliv and Band[9]). In table 2 we compare our values to those of ref. 2 and of El-Nesr and Bashandy[10]) by using the normalized value 6.7% for the population of the 321-keV level. Our data, so normalized, are in agreement with those of Alexander et al, but differ from the data of El-Nesr and Bashandy.

## 3. $^{177}Lu^{m}$

In figs. 1, 2, 3, and 4 we show the gamma-ray spectrum of 155-day $^{177}Lu^{m}$ taken with the Ge(Li) detector. The 426-keV gamma ray found by Blok and Shirley[3,4]) is easily seen in this spectrum. A close examination of fig. 3 indicates that both the 282- and 292-keV peaks are complex. Careful analysis of these peaks using the shape of the 269-keV gamma ray as a standard showed that the peak at 282 keV is composed of gammas of 281.8 and 283.4 keV, and the peak at 292 keV is composed of gammas of 291.4 and 292.5 keV. From energy considerations, the 283.4-keV transition can be assigned as the $^{177}$Hf interband transition from the 21/2+(K=9/2) to the 19/2-(K=7/2) levels, the 291.4 as the interband 17/2+(K=9/2) to 15/2-(K=7/2) transition, and the 292.5 as the 19/2+(K=9/2) to 17/2-(K=7/2) transition.

In fig. 5 we show a weak gamma ray found at 182.0 keV. This transition fits energetically as the cascade transition from the 15/2- to the 13/2-levels within the $^{177}$Hf K = 7/2- band.

Both figs. 1 and 6 show evidence for a weak gamma at 69.2 keV that may correspond to the $^{177}$Hf interband transition between the 19/2 + (K = 9/2) and the 19/2- (K = 7/2) levels. Further study is being undertaken in an attempt to confirm this assignment.

We do not observe the 41.0-keV transition reported by Bodenstedt et al.[5]). If this transition is present with the intensity reported by them, it should easily have been observed in our spectrum, for the photopeak efficiency of our Ge(Li) detector is approximately 30% greater and the resolution more than a factor of 2.5 better than that of the detector used in ref. 5. In fig. 6 we show the low energy portion of our $^{177}Lu^{m}$ spectrum. From this spectrum we place an upper limit of 0.8% on the intensity of the 41.0- relative to the 105.3-keV transition. The peaks at 24.1 and 27.6 keV arise from x rays generated in the indium foil used as an electrical and thermal contact between the Ge(Li) detector and its copper mounting block.

Table 3 contains a summary of our energy and relative intensity values for the gamma rays emitted in the decay of $^{177}Lu^{m}$. The values given in ref. 2 are included for comparison. It should be noted that, with the exception of five transitions, both sets of energy measurements are consistent within the combined error limits. Our energy values have been determined by careful calibration of the pulse-height spectrum, taking into account non-linearities in the detection system by a method described elsewhere[9]). We used as standards those gamma rays listed in table 4. As is seen in this table, we utilize as standards some of the prominent transitions which appear in both the gamma-ray spectrum from neutron-capture in $^{176}Lu$ and in the spectrum from the decay of $^{177}Lu^{m}$. In general, our energy values have good internal consistency. For example, below we show the various sum and difference relationships for the transition between the $I = 13/2 + (K = 9/2+)$ and $I = 11/2 - (K = 7/2-)$ levels in $^{177}Hf$.

$$71.66 + 233.83 = 305.49 \text{ keV}$$
$$128.50 + 177.03 = 305.53 \text{ "}$$
$$145.78 + 159.75 = 305.53 \text{ "}$$
$$117.17 + 341.64 - 153.29 = 305.52 \text{ "}$$
$$128.50 + 313.69 - 136.72 = 305.47 \text{ "}$$
$$233.83 + 208.34 - 136.72 = 305.45 \text{ "}$$
$$233.83 + 321.32 - 249.65 = 305.50 \text{ "}$$
$$291.42 + 341.64 - 327.66 = 305.40 \text{ "}$$
$$299.03 + 159.75 - 153.29 = 305.49 \text{ "}$$
$$\text{Measured energy} = 305.52 \text{ "}$$

Not included in table 3 are additional weak lines at about 168.4, 262.9, 264.1, 337.1, 432.4, 433.7, 436.4, 439.9, 441.9, and 473.7 keV which appeared in the $^{177}Lu^m$ spectrum with intensities two percent or less relative to that of the 105.3-keV transition. It has been noted in spectra taken with larger source-to-detector distances that the relative intensities of these peaks are significantly reduced. This supports our interpretation of these lines as arising from "solid-angle summing" of the K x rays with prominent gamma rays.

The decay scheme of $^{177}Lu^m$ is shown in fig. 7. This is essentially the scheme proposed by Alexander et al.[2]), with additions from refs. 3, 5, and the present work.

## 4. Discussion

### 4.1 Branching Ratios within Bands and g-Factors

Alexander et al.[2]) have pointed out that the copious intensity data on $^{177}Lu^m$ provide a good opportunity to test the quantity $|g_K - g_R|$

which, according to the rotational model, should have a constant value for all states in an unperturbed rotational band. The relevant equations for calculating the quantity $[(g_K - g_R)/Q_o]^2$ from the cascade-to-crossover photon ratios are given in their paper. Their analysis shows that, in each of the three rotational bands populated by the decay of $^{177}Lu^m$, this quantity is constant within the limits of error. Because of the somewhat higher accuracy of our intensity data we have repeated these calculations, and table 5 presents the new results together with those of Alexander et al.[2]).

The conclusions of Alexander et al. with respect to the K = 7/2+[404] band in $^{177}Lu$ are unaltered. We find a constant value of $[(g_K - g_R)/Q_o]^2$ for all states in this band, and our average value of this quantity, $(2.53 \pm 0.28) \times 10^{-3}$, is very similar to that of Alexander et al.

Also for the 9/2+[624] band in $^{177}Hf$ we obtain essentially constant values of $[(g_K - g_R)/Q_o]^2$, and the average value is $(2.82 \pm 0.15) \times 10^{-3}$. If we use for $Q_o$ the value 6.85 obtained from the Coulomb excitation of the K = 9/2+ band in $^{197}Hf$[15]), we find $|g_K - g_R| = 0.364 \pm 0.014$, which corresponds closely to the value 0.376±0.025 reported by Bernstein and deBoer[16]) for the analogous band in $^{179}Hf$.

In the case of the 7/2-[514] band in $^{177}Hf$, the magnetic transition probability is small, and Alexander et al. report $|g_K - g_R| \leq 0.03$. We obtain in this case the average value $[(g_K - g_R)/Q_o]^2 = (1.81^{+0.75}_{-0.51}) \times 10^{-4}$. Using $Q_o = 6.74$[13]) we find $|g_K - g_R| = 0.089 \pm 0.023$ for this band.

4.2 E1 Transitions in $^{177}Hf$

One of the unusual aspects of the decay of $^{177}Lu^m$ is the large number of interband electric dipole transitions that are observed to take place between levels of the K = 9/2 + [614] band and those of the 7/2 - [514] band in $^{177}$Hf. Ten E1 transitions were reported by Alexander et al., and, as mentioned in section 3, we have identified two additional E1 transitions in this study, and have made measurements of their energies and intensities.

The transition rates of electric dipole transitions in deformed nuclei have not been satisfactorily described by any quantitative theory. The fact of their high retardation was discussed by Strominger and Rasmussen[18]) who showed that the large wave function components of the E1 transition matrix element are in general forbidden by the asymptotic selection rules based on the Nilsson rules

and that the hindrance of the transition rates results from a near-cancellation of the various small-component contributions. More recently Vergnes and Rasmussen[19]) have shown that the influence of the pairing correlation cannot provide a satisfactory and consistent explanation for the observed E1 transition rates.

The question of the contributions to the E1 transition probabilities from Coriolis admixed components (RPC) in the wave functions has been considered by Grin and Pavlichenkov[20,21]) as well as by Vergnes and Rasmussen[18]). As pointed out by those authors, it is useful in this regard to study the branching ratios of E1 transitions between pairs of rotational bands because deviations from the simple geometric branching ratio rules must be interpreted in terms of contributions to the transition probabilities from admixed wave function components. With particular reference to $^{177}$Hf, both groups of authors have provided evidence from perturbation treatment of the Coriolis interaction that the simple assumption of a $K = 7/2+$ component admixed into the predominent $K = 9/2 + [624]$ band of $^{177}Hf$ yields branching ratios in fairly good agreement with the values observed by Alexander et al.[2]. Vergnes and Rasmussen[19] in a method similar to that used by Grin and Pavlichenkov[21] calculate the E1 transition probabilities from the admixed band with use of the following expression:

$$B(E1) \propto \left| \mu_9 (I_i 1\ 9/2\ -1 | I_f\ 7/2) + P_7 \sqrt{I_i(I_i+1)-(7/2)(9/2)}\ (I_i 1\ 7/2\ 0\ | I_f\ 7/2) \right|^2$$

in which $\mu_9$ is the E1 matrix element for the dominant $K_i = 9/2+$ component and $P_7$ is assumed simply to be the product of the RPC matrix element, the E1 matrix element from the $K = 7/2+$ component, and the factor $\frac{\hbar^2}{2\mathcal{J}(E_{9/2} - E_{7/2})}$ arising from the first order perturbation treatment. The experimental transition probabilities of the 321- and 208-keV transitions were used to fix the parameters $\mu_9$ and $P_7$.

We have now used our data for a similar calculation, and the results are shown in Tables 6 and 7. Our values for the theoretical transition probabilities differ from those of Vergnes and Rasmussen because we did not assign an experimental intensity of zero to the 321-keV transition and because our measured intensity for the 208-keV gamma ray is ~15% lower than the intensity given by Alexander et al. In Table 6 are given the calculated theoretical E1 transition rates and the experimental rates found by Alexander et al.[2] and in this work. In Table 7 the branching ratios are shown, in comparison with the simple geometric ratios of Alaga[22] and with the theoretical ratios of Vergnes and Rasmussen[19].

It is to be noted from tables 3 and 6 that our measurements yielded a value for the intensity of the 117-keV transition significantly different from that obtained by Alexander et al., and table 7 shows that this change has apparently removed the only case of serious disagreement between theory and experiment.

Identification of the 291.3 and 283.4 keV gamma rays representing the $17/2 \rightarrow 15/2$ and $21/2 \rightarrow 19/2$ interband transitions has reduced to at most four the number of unobserved E1 transitions leading from the known states of the K = 9/2+ band to the 7/2- band in $^{177}$Hf. As previously mentioned, a very weak line that may correspond to the 69.2-keV E1 is seen in our spectrum. Theoretical transition probabilities were calculated for the three E1's at 17.2-, 41.0-, and 88.4-keV.

The predicted branching ratios for the unobserved E1 transitions indicate that the 17.2, 41.0, and 69.2 keV E1's are at or below the minimum intensity limit detectable with presently available systems. They should have intensities of only about 0.02, 0.009, and 0.09 percent, respectively, relative to the 105.4-keV gamma. On the basis of the weak line observed at 69.2 keV, we have made a tentative intensity assignment to this E1. The corresponding branching ratio would seem to agree quite well with the simple theoretical prediction. Although the 88.4-keV E1 has a predicted relative intensity of ~0.3%, no evidence was found to indicate its presence. It should be emphasized that these theoretical extrapolations are assumed to have some validity because the present experimental ratio of the reduced transition rates for the $15/2 \rightarrow 15/2$ and the $15/2 \rightarrow 13/2$ gammas is now in good agreement with calculations involving Coriolis admixing.

Table 6 shows that although the calculated absolute transition probabilities $(T(E1)/T_W(E1)$ begin to exhibit increasing positive disagreement with experiment for spins greater than 13/2 (because of the predominance of the spin-dependent square root term in the Coriolis matrix element), nevertheless the predicted branching ratios shown in table 7 still agree fairly well with experiment at least through $I_i = 15/2$.

Further work is presently being undertaken on high resolution anti-Compton equipment to obtain at least first-order intensity measurements for the 69.2- and 88.4-keV gamma rays. These additional E1 transition intensities would provide more branching ratios and thus a further experimental test of the apparent necessity to consider Coriolis admixing in any comprehensive treatment of $\Delta K = \pm 1$ E1 transitions in deformed odd-mass nuclei.

We wish to thank Prof. J. O. Rasmussen for many helpful discussions.

References

1) M. Jorgensen, O. B. Nielsen, and G. Sidenius, Phys. Letters 1 (1962) 321

2) P. Alexander, F. Boehm, and E. Kankeleit, Phys. Rev. 133 (1964) B284

3) J. Blok and D. A. Shirley, Phys. Letters 13 (1964) 232

4) J. Blok (Ph.D. Thesis), Lawrence Radiation Laboratory Report UCRL-16279, 1965 (unpublished)

5) E. Bodenstedt, J. Radeloff, N. Buttler, P. Meyer, L. Shanzler, M. Forker, H. F. Wagner, K. Krein, and K. G. Plingen, Zeitschrift für Physik 190 (1966) 60

6) E. Elad, Nucl. Instr. Methods 37 (1965) 327

7) P. Marmier and F. Boehm, Phys. Rev. 97 (1955) 103

8) Nuclear Data Sheets, Nuclear Data Group, Oak Ridge, Tennessee

9) L. A. Sliv and I. M. Band, "Alpha-, Beta-, and Gamma-Ray Spectroscopy," ed. by K. Siegbahn, (North-Holland Publishing Co., Amsterdam, 1965) 1639

10) M. S. El-Nesr and E. Bashandy, Nucl. Phys. 31 (1962) 128

11) A. J. Haverfield, (Ph.D. Thesis), Lawrence Radiation Laboratory Report UCRL-16969, 1966 (unpublished)

12) B. Elbek, M. C. Olesen, and O. Skilbreid, Nucl. Phys. 10 (1959) 294

13) J. deBoer and J. D. Rogers, Phys. Letters 3 (1963) 304

14) J. Lindskog, T. Sundstrom, and P. Sparrman, Arkiv Fysik 23 (1962) 341

15) O. Hansen, M. C. Oleson, O. Skilbreid, and B. Elbek, Nucl. Phys. 25 (1961) 634

16) E. M. Bernstein and J. deBoer, Nucl. Phys. 18 (1960) 40

17) S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 29 No. 16 (1954)

18) D. Strominger and J. O. Rasmussen, Nucl. Phys. 3 (1957) 197

19) M. N. Vergnes and J. O. Rasmussen, Nucl. Phys. 62 (1965) 233

20) Yu. T. Grin and I. M. Pavlichenkov, Phys. Letters 9 (1964) 249

21) Yu. T. Grin and I. M. Pavlichenkov, Nucl. Phys. 65 (1965) 686

22) G. Alaga, K. Alder, A. Bohr, and B. Mottelson, Mat. Fys. Medd. Dan. Vid. Selsk. 29 No. 9 (1955)

## Figure Captions

Fig. 1. Gamma spectrum of $^{177}Lu^{m}$ in the energy region 40 to 150 keV as observed on a Ge(Li) detector. The gamma rays are identified by their energies in keV.

Fig. 2. Gamma spectrum of $^{177}Lu^{m}$ in the energy region 150 to 255 keV.

Fig. 3. Gamma spectrum of $^{177}Lu^{m}$ in the energy region 255 to 360 keV.

Fig. 4. Gamma spectrum of $^{177}Lu^{m}$ in the energy region 360 to 470 keV.

Fig. 5. Weak 182-keV gamma ray from the decay of $^{177}Lu^{m}$.

Fig. 6. Gamma spectrum of $^{177}Lu^{m}$ in the energy region 0 to 108 keV.

Fig. 7. Decay scheme of $^{177}Lu^{m}$ taken from ref. 2 with additions from refs. 3,4 and the present work.

Table 1

Relative intensities of gamma rays from 7-day $^{177}Lu$

| Gamma-ray Energy (keV) | Relative Intensity | | |
| --- | --- | --- | --- |
| | Present Work | Alexander et al[2]) | Marmier and Boehm[7]) |
| 71.66 | 2.4 (1) | 2.4 (1) | 2.0 (4) |
| 112.95 | 100 | 100 | 100 |
| 136.72 | 0.92 (6) | 0.74 (4) | --- |
| 208.34 | 164 (10) | 171 (9) | 220 (44) |
| 249.65 | 3.0 (2) | 3.3 (2) | 3.0 (6) |
| 321.32 | 3.6 (2) | 3.4 (2) | 3.2 (6) |

Table 2

β-decay branchings from decay of 7-day $^{177}Lu$ into states of spin I in $^{177}Hf$

| K | I | Percent Branching | | |
|---|---|---|---|---|
| | | Present Work | Alexander et al[2]) | El-Nesr and Bashandy[10]) |
| 7/2 | 7/2- | 87.2±1.1 | 86.3±1.3 | 90± 4 |
| | 9/2- | 6.0±0.8 | 7±1 | 2.95±0.05 |
| | 11/2- | 0.07±0.02 | 0.03±0.03 | 0.31±0.06 |
| 9/2 | 9/2+ | 6.7±0.3 | 6.7±0.3 | 6.72±0.25 |

Table 3

Energies and relative intensities of gamma rays from the decay of 155-day $^{177}Lu^m$

| Present work | | Alexander et al.[2] | |
|---|---|---|---|
| Gamma-ray energy (keV) | Relative intensity | Gamma-ray energy (keV) | Relative intensity |
| 69.19 | (0.08) | | |
| 71.66 (6) | 6.8 (4) | 71.64 (2) | 9 (2) |
| 105.31 (5) | 100* | 105.36 (2) | 100* |
| 112.95 (5) | 179 (13) | 112.97 (2) | 251 (13) |
| 115.96 (10) | 5.0 (4) | 115.83 (4) | 9 (2) |
| 117.17 (13) | 1.8 (2) | 117.01 (4) | 12 (2) |
| 121.63 (5) | 52 (4) | 121.56 (3) | 62 (3) |
| 128.50 (5) | 127 (8) | 128.48 (2) | 125 (6) |
| 136.72 (5) | 11.7 (8) | 136.68 (2) | 17 (3) |
| 145.78 (10) | 6.6 (9) | 145.59 (6) | 11 (2) |
| 147.15 (8) | 29 (2) | 147.10 (6) | 27 (3) |
| 153.29 (6) | 133 (8) | 153.25 (4) | 134 (7) |
| 159.75 (8) | 5.4 (5) | 159.92 (8) | 5 (1) |
| 171.85 (10) | 37 (4) | 171.84 (8) | 41 (4) |
| 174.42 (6) | 96 (8) | 174.37 (6) | 110 (6) |
| 177.03 (8) | 26 (3) | 177.05 (8) | 34 (3) |
| 181.98 (10) | 0.75 (13) | | |
| 195.52 (6) | 7.0 (6) | 195.4 (1) | 9 (2) |
| 204.08 (6) | 114 (8) | 204.00 (8) | 130 (13) |
| 208.34 (6) | 485 (40) | 208.36 (6) | 610 (31) |
| 214.45 (6) | 48 (4) | 214.3 (1) | 79 (8) |
| 218.06 (6) | 27 (3) | 218.0 (1) | 37 (6) |
| 228.44 (6) | 287 (26) | 228.48 (8) | 340 (17) |
| 233.83 (6) | 45 (4) | 233.75 (10) | 43 (4) |
| 249.65 (6) | 47 (4) | 249.69 (10) | 62 (6) |

(continued)

Table 3. Continued

| Present work | | Alexander et al.[2]) | |
|---|---|---|---|
| Gamma-ray energy (keV) | Relative intensity | Gamma-ray energy (keV) | Relative intensity |
| 268.79 (6) | 25 (3) | 268.4 (1) | 32 (5) |
| 281.78 (7) | 108 (9) | 281.77 (10) | 121 (6) |
| 283.42 (13) | 4.7 (1.2) | | |
| 291.42 (10) | 7.7 (9) | } 291.7 (3) | 20 (4) |
| 292.51 (10) | 7.8 (9) | | |
| 296.45 (8) | 38 (4) | 296.1 (2) | 65 (7) |
| 299.03 (10) | 12 (2) | 299.1 (3) | 10 (2) |
| 305.52 (8) | 14 (1) | 306.0 (3) | 13 (3) |
| 313.69 (8) | 9.4 (7) | 313.5 (3) | 12 (2) |
| 318.98 (8) | 78 (8) | 318.8 (2) | 86 (4) |
| 321.32 (12) | 9 (1) | 321.4 (2) | ≤12 |
| 327.66 (8) | 136 (8) | 327.7 (3) | 149 (15) |
| 341.64 (8) | 13 (1) | 341.8 (4) | 14 (4) |
| 367.41 (8) | 23 (2) | 367.4 (4) | 25 (5) |
| 378.51 (8) | 222 (17) | 378.4 (3) | 223 (22) |
| 385.02 (8) | 24 (2) | 385.0 (4) | 37 (7) |
| 413.64 (12) | 131 (10) | 413.7 (5) | 163 (16) |
| 418.51 (10) | 161 (12) | 418.6 (5) | 185 (19) |
| 426.29 (10) | 3.4 (4) | | |
| 465.96 (12) | 19 (2) | 466 (1) | 23 (7) |

*Normalized to 100 units

Table 4

Gamma-ray energy standards used in spectrometer calibration

| Source | Gamma-ray energy (kev) | Reference |
|---|---|---|
| $^{241}Am$ | 59.543±0.015 | a |
| $^{203}Hg$ (Tl $K_{\alpha_2}$ x ray) | 70.832 | |
| (Tl $K_{\alpha_1}$ x ray) | 73.172 | |
| $^{177}Lu^m$ | 112.952±0.003 | b |
| | 121.620±0.003 | b |
| $^{57}Co$ | 121.97 ±0.03 | c |
| | 136.33 ±0.03 | c |
| $^{177}Lu^m$ | 147.165±0.005 | b |
| | 208.359±0.010 | b |
| | 268.801±0.014 | b |
| $^{203}Hg$ | 279.16 ±0.02 | d |
| $^{131}I$ | 284.307±0.049 | e |
| | 364.467±0.050 | e |
| $^{198}Au$ | 411.795±0.009 | f |
| $m_oc^2$ | 511.006±0.002 | |

a) T. Yamazaki and J. M. Hollander, Nuclear Phys. 84 (1966) 505

b) Bernd P. K. Maier, Z. Physik 184, (1965) 153

c) J. M. Marion, private communication

d) C. J. Herrlander and R. L. Graham, Nuclear Phys. 58, (1964) 544

e) H. C. Hoyt and J. W. M. DuMond, Phys. Rev. 91 (1953) 1027

f) G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. 63, (1965) 353

Table 5

Branching ratios and g factors for the K = 7/2+[404] rotational band in $^{177}Lu$ and the K = 7/2-[514] and K = 9/2+[624] bands in $^{177}Hf$. λ is the experimental crossover to cascade ratio where I is the initial spin state. $Q_0$ is the intrinsic quadrupole moment for the nucleus in spin state I, and $g_K - g_R$ is associated with transitions I→I-1. $1/\delta^2$ is the M1/E2 branching ratio for I→I-1 cascade transitions.

| | I | λ | | $[(g_K-g_R)/Q_0]^2 \times 10^3$ | | $1/\delta^2$ | |
|---|---|---|---|---|---|---|---|
| | | Present work | Alexander et al.[2] | Present work | Alexander et al.[2] | Present work | Alexander et al.[2] |
| $^{177}Lu$ | | | | | | | |
| K = 7/2+ | 11/2 | 0.86±0.12 | 1.19±0.21 | 2.6 ±0.4 | 1.7±0.5 | 4.0 | 2.6 |
| | 13/2 | 2.1 ±0.3 | 2.10±0.25 | 2.4 ±0.3 | 2.4±0.35 | 4.0 | 3.8 |
| | 15/2 | 3.3 ±0.4 | 2.8 ±0.8 | 2.6 ±0.3 | 3.2±1.0 | 4.3 | 5.6 |
| | 17/2 | 4.9 ±0.7 | 4.7 ±0.8 | 2.5 ±0.4 | 2.8±0.6 | 4.4 | 4.8 |
| $^{177}Hf$ | | | | | | | |
| K = 7/2- | 11/2 | 4.0 ±0.4 | 4.5 ±0.3 | $0.043^{+.068}_{-.043}$ | <0.002 | 0.077 | <0.035 |
| | 13/2 | 7.0 ±1.0 | 13±3 | $0.26^{+.14}_{-.10}$ | <0.001 | 0.48 | <0.02 |
| | 15/2 | 17.3 ±3.3 | >7 | $0.24^{+.16}_{-.11}$ | <0.007 | 0.45 | <1.3 |
| $^{177}Hf$ | | | | | | | |
| K = 9/2+ | 13/2 | 0.35±0.04 | 0.34±0.04 | 2.7 ±0.3 | 2.8±0.4 | 7.8 | 8.0 |
| | 15/2 | 0.81±0.08 | 0.90±0.07 | 2.8 ±0.3 | 2.5±0.2 | 7.6 | 6.8 |
| | 17/2 | 1.42±0.14 | 1.35±0.16 | 2.9 ±0.3 | 3.0±0.4 | 7.8 | 8.1 |
| | 19/2 | 1.95±0.20 | 1.72±0.23 | 3.0 ±0.3 | 3.5±0.5 | 7.5 | 8.6 |
| | 21/2 | 3.35±0.42 | 2.33±0.35 | 2.7 ±0.3 | 4.1±0.6 | 7.4 | 11.0 |

Table 6

E1 transition rates between the K = 9/2+ and K = 7/2- bands in $^{177}Hf$ (Weisskopf Units)

| $I_i$ | $I_f$ | $E_\gamma$ | $\frac{T(E1)}{T_W(E1)^a} \times 10^5$ Experimental This Work | Experimental Alexander[2] | Theory After ref[19] |
|---|---|---|---|---|---|
| 9/2 | 7/2 | 321.3 | 0.012[b] | 0.013 | -- |
| 9/2 | 9/2 | 208.3 | 2.4[b] | 3 | -- |
| 9/2 | 11/2 | 71.7 | 0.81[b] | 1.2 | 1.1 |
| 11/2 | 9/2 | 313.7 | 0.15[c] | 0.5 | 0.28 |
| 11/2 | 11/2 | 177.0 | 2.2[c] | 7 | 3.6 |
| 11/2 | 13/2 | (17.2) | -- | -- | 2.9 |
| 13/2 | 11/2 | 305.5 | 0.52[d] | 0.9 | 1.2 |
| 13/2 | 13/2 | 145.8 | 2.3[d] | 7 | 4.4 |
| 15/2 | 13/2 | 299.0 | 1.0[e] | 0.6 | 2.7 |
| 15/2 | 15/2 | 117.2 | 2.5[e] | 12 | 4.9 |
| 17/2 | 15/2 | 291.4 | 1.7[f] | -- | 4.4 |
| 17/2 | 17/2 | (88.4) | -- | -- | 5.2 |
| 19/2 | 17/2 | 292.5 | 2.5[g] | 3 | 6.8 |
| 19/2 | 19/2 | (69.2) | (2)[g] | -- | 5.5 |
| 21/2 | 19/2 | 283.4 | 4.5[h] | -- | 9.3 |
| 21/2 | 21/2 | (41.0) | -- | -- | 5.7 |

[a] $T_W(E1)$ is the "Weisskopf estimate" $T(E1) = 1.5 \times 10^5 A^{2/3} E_\gamma^3$ in keV and sec.

[b] Based on $\tau_{1/2} = 6.3 \times 10^{-10}$ sec. of the 321-keV state

[c] Based on the rotational transition rate for the 105.3-keV transition, with $[g_K - g_R/Q_0]^2 = 2.8 \times 10^{-3}$ and $Q_0(K=9/2) = 6.85$ barns.

[d] Based on the rotational electric quadrupole transition rate T(E2) of the 233.8-keV transition from the 13/2 state. ($Q_0 = 6.85$ barns).

[e] Based on T(E2) of the 281.8-keV transition.

[f] Based on T(E2) of the 327.7-keV transition.

[g] Based on T(E2) of the 378.5-keV transition.

[h] Based on T(E2) of the 418.5-keV transition.

Table 7

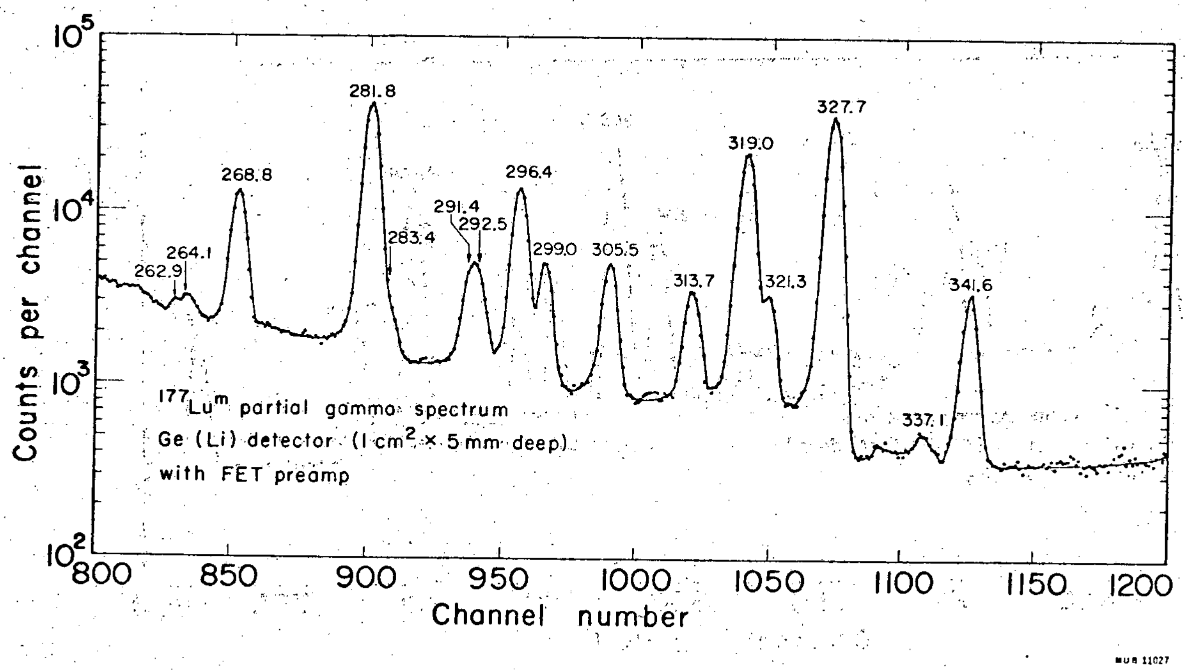
Relative reduced strengths for E1 transitions from the K = 9/2+ to K = 7/2- bands in $^{177}$Hf

| $I_i$ | $I_f$ | $I'_f$ | $\frac{Int_\gamma}{Int_{\gamma'}}$ | $\frac{B(E1)\ I_i \to I_f}{B(E1)\ I_i \to I'_f}$ Experiment: This Work | Experiment: Alex.[2] | Theory: Alaga ‡ | Theory: After ref19) |
|---|---|---|---|---|---|---|---|
| 9/2 | 9/2 | 7/2 | 54 | 200 | 175 | 0.23 | 200* |
| 9/2 | 11/2 | 9/2 | 0.014 | 0.35 | 0.37 | 0.10 | 0.48 |
| 11/2 | 11/2 | 9/2 | 2.8 | 15.4 | 15.8 | 0.41 | 13 |
| 11/2 | 13/2 | 11/2 | 0.0008† | | | 0.14 | 0.79 |
| 13/2 | 13/2 | 11/2 | 0.47 | 4.4 | 7.7 | 0.56 | 3.7 |
| 15/2 | 15/2 | 13/2 | 0.15 | 2.5 | 20 | 0.70 | 1.9 |
| 17/2 | 17/2 | 15/2 | 0.033† | | | 0.79 | 1.2 |
| 19/2 | 19/2 | 17/2 | (0.01) | (1.) | | 0.88 | 0.81 |
| 21/2 | 21/2 | 19/2 | 0.002† | | | 0.96 | 0.61 |

*Assumed value for fixing parameters.

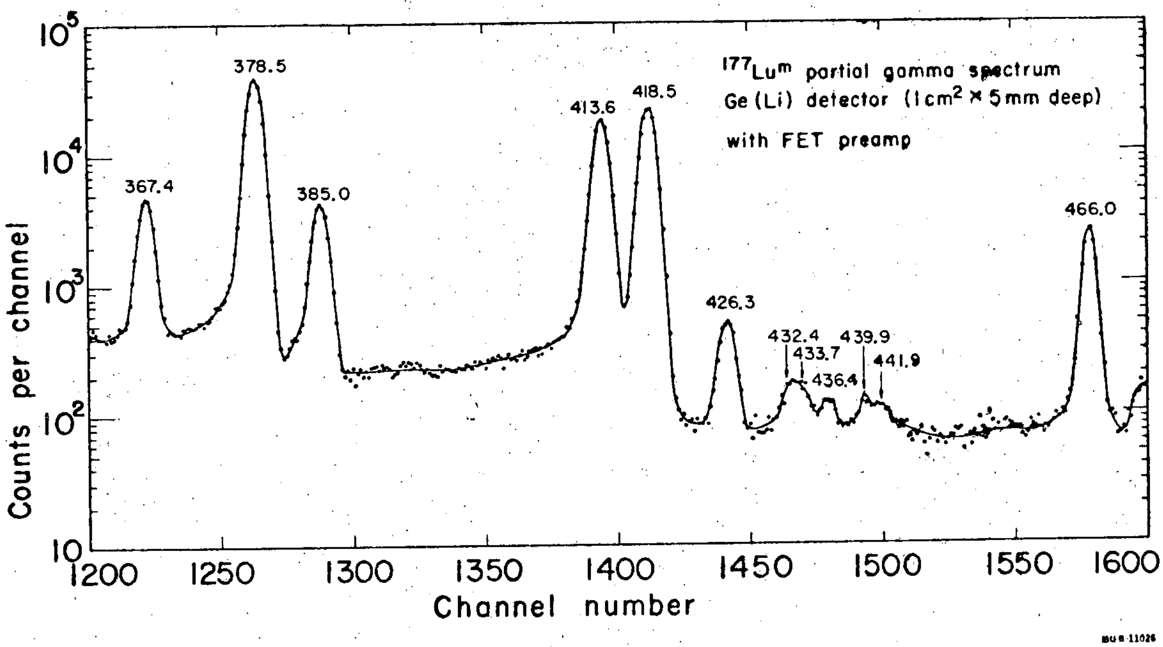
†Indicates theoretical ratios, in cases where one of the gamma rays is unobserved.

‡Alaga's rule for branching between members of two rotational bands is the squared ratio of Clebsch Gordan Coefficients $[(I_i 1\ K_i\ -1 \mid I_f\ K_f)/(I_i 1\ K_i\ -1 \mid I'_f\ K_f)]^2$.



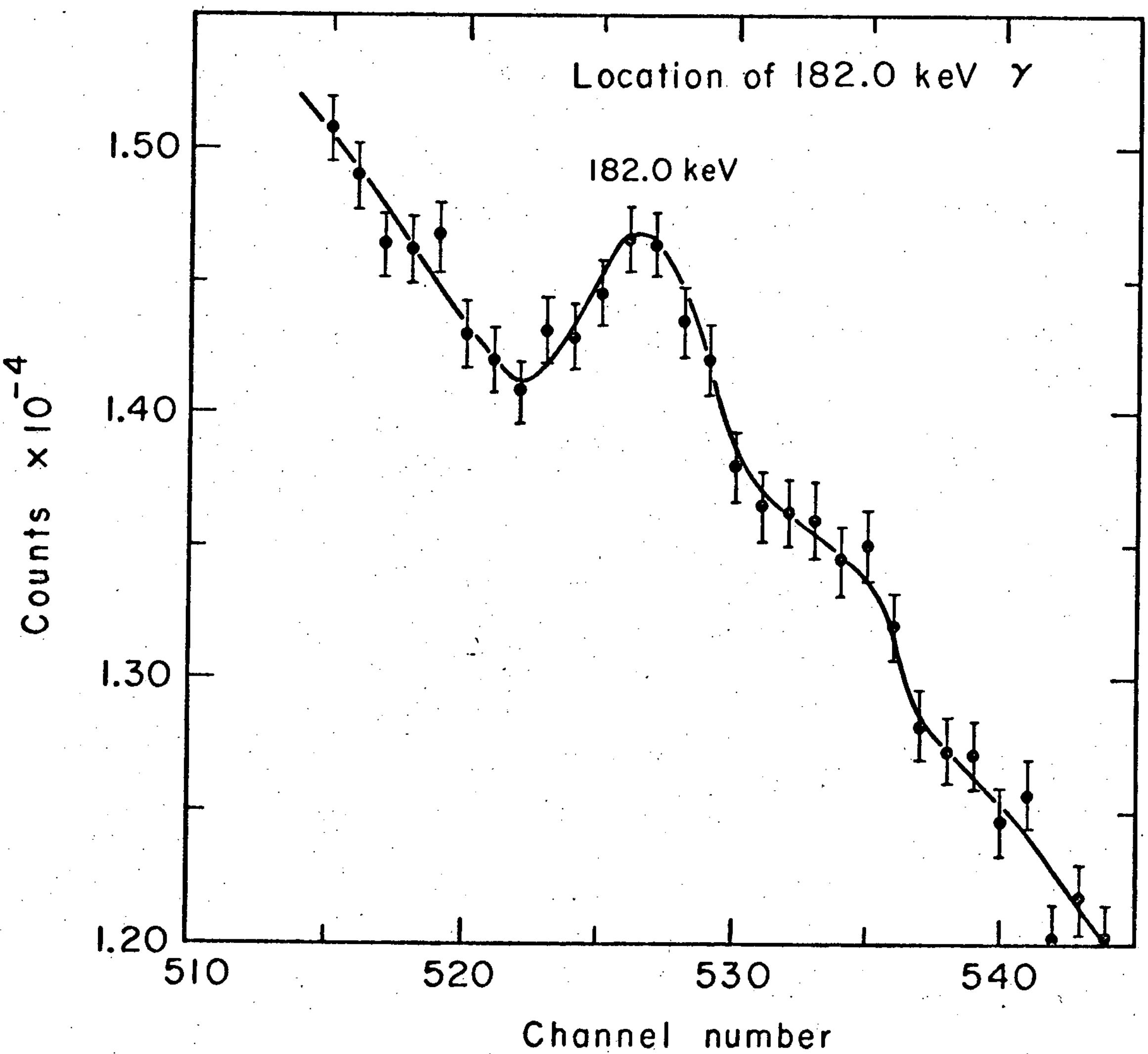
Counts per channel
$10^5$
$10^4$
$10^3$
$10^2$
281.8
327.7
319.0
268.8
296.4
291.4
292.5
283.4
264.1
262.9
299.0
305.5
313.7
321.3
341.6
337.1
$^{177}Lu^m$ partial gamma spectrum
Ge (Li) detector (1 cm$^2$ × 5 mm deep)
with FET preamp
800
850
900
950
1000
1050
1100
1150
1200
Channel number
MUB 11027


Fig. 3



$^{177}$Lu$^m$ partial gamma spectrum
Ge (Li) detector (1 cm$^2$ × 5 mm deep)
with FET preamp
367.4
378.5
385.0
413.6
418.5
426.3
432.4
433.7
436.4
439.9
441.9
466.0
Counts per channel
Channel number
10
$10^2$
$10^3$
$10^4$
$10^5$
1200
1250
1300
1350
1400
1450
1500
1550
1600


Fig. 4




MUB-11024

Fig. 5

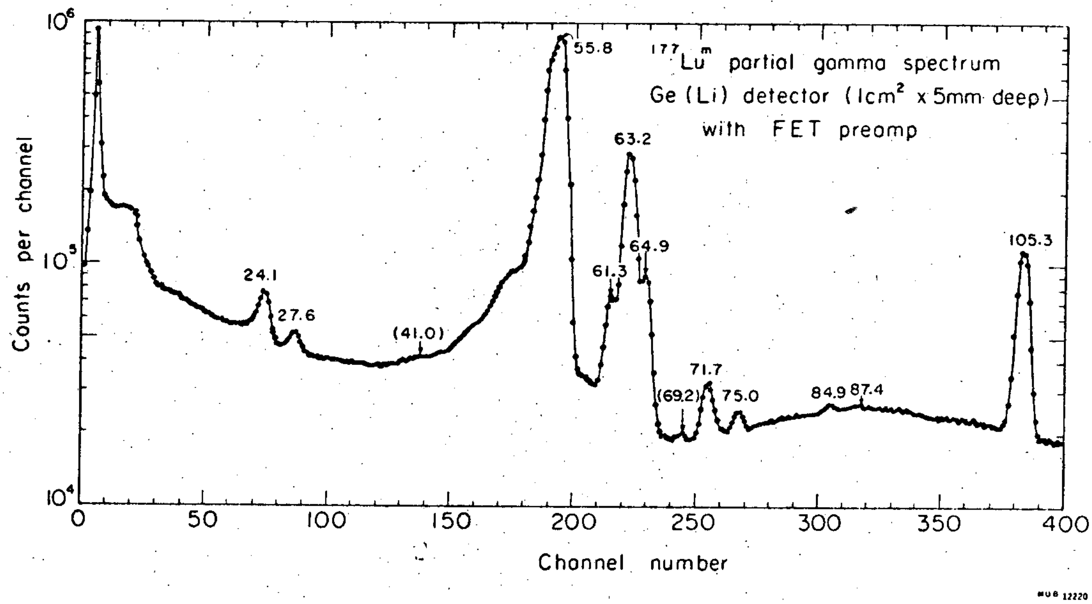

$^{177}Lu^m$ partial gamma spectrum
Ge (Li) detector (1cm² x 5mm deep)
with FET preamp
Counts per channel
Channel number
55.8
63.2
64.9
61.3
24.1
27.6
(41.0)
71.7
(69.2)
75.0
84.9
87.4
105.3
$10^6$
$10^5$
$10^4$
0
50
100
150
200
250
300
350
400
MUB 12220

Fig. 6

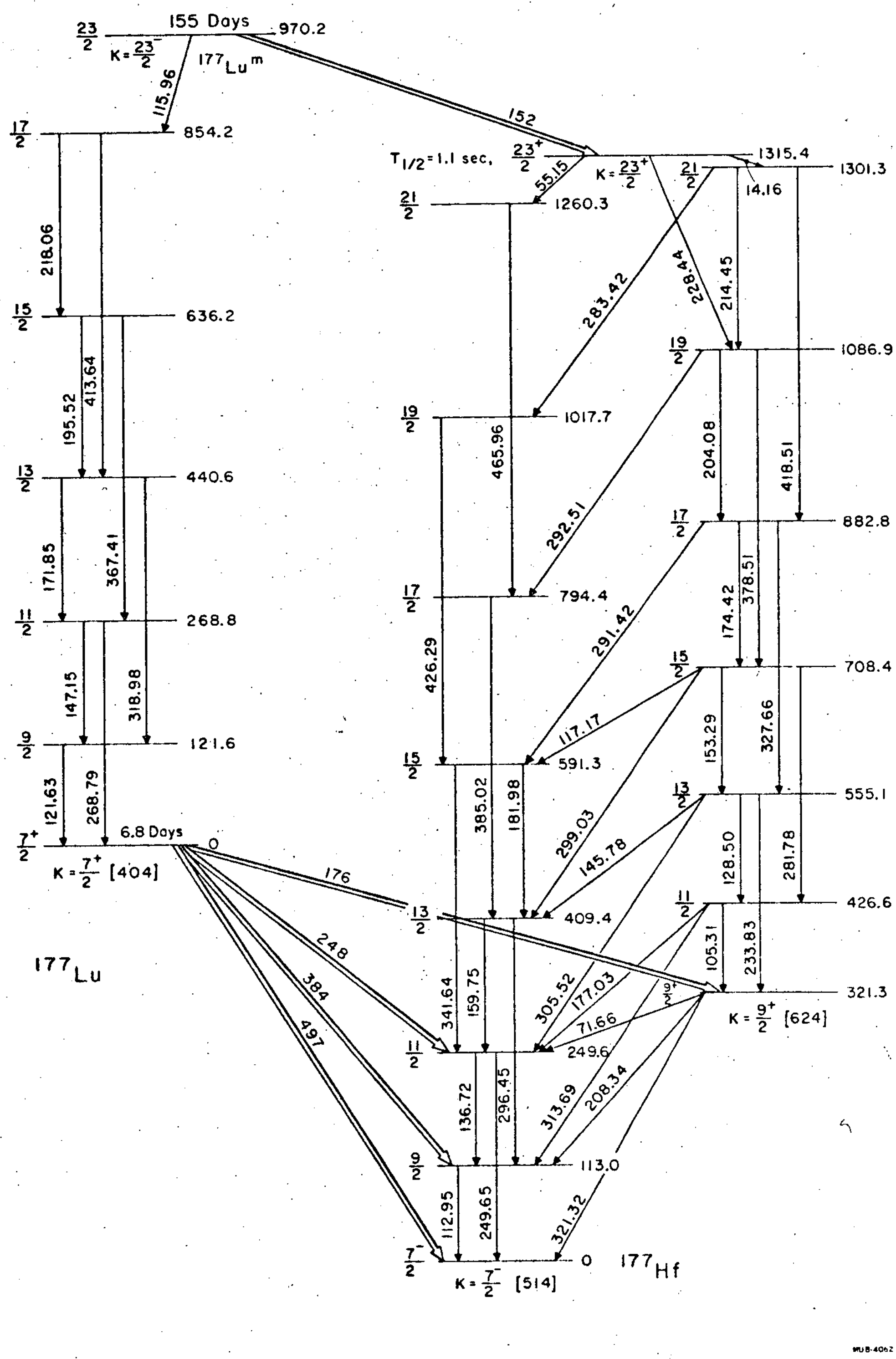

155 Days
970.2
K = 23⁻/2
177Luᵐ
115.96
854.2
636.2
440.6
268.8
121.6
218.06
195.52
413.64
171.85
367.41
147.15
318.98
121.63
268.79
6.8 Days
0
K = 7⁺/2 [404]
177Lu
152
T1/2 = 1.1 sec.
55.15
1260.3
1315.4
K = 23⁺/2
14.16
1301.3
283.42
228.44
214.45
1086.9
1017.7
465.96
204.08
418.51
292.51
882.8
794.4
291.42
174.42
378.51
426.29
708.4
117.17
591.3
153.29
327.66
385.02
181.98
299.03
145.78
555.1
128.50
281.78
176
409.4
426.6
248
384
497
341.64
159.75
305.52
177.03
105.31
233.83
321.3
71.66
K = 9⁺/2 [624]
249.6
136.72
296.45
313.69
208.34
113.0
112.95
249.65
321.32
0
K = 7⁻/2 [514]
177Hf
MUB-4062-B

Fig. 7