University of California

Ernest O. Lawrence Radiation Laboratory

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ABSTRACT

A level scheme for ^{154}Dy is proposed from study of the β-decay of ^{154}Ho, and from the "in-beam" gamma spectrum of the reaction ^{139}La(^{19}F,4n)^{154}Dy. The ground-state quasirotational band is observed up to spin 10^+ in the reaction, and up to 8^+ in the β-decay. It is proposed that the other levels observed in the β-decay may be understood as a quasi β-vibrational band.

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‡Current address: Rutgers University, New Brunswick, New Jersey.

1. Introduction

Experiments in (HI,xn) reaction gamma-ray spectroscopy have been performed extensively in recent years by various groups[1]. In addition to providing information on the final reaction product by "in-beam" gamma-ray spectroscopy, it should also be possible to obtain information on the nuclei which follow the in-beam product by successive β-decays. If the accelerator has a pulsed operation, the gamma spectra of such decays can be obtained at the same time as the "in-beam" spectra by gating the analyzer. In this way a useful "first look" at the gamma-rays associated with the β-decays can be obtained. In recent work at the Berkeley Hilac (beam-bursts of 5 msec. duration at 40 bursts per sec.) these techniques have been applied to the decays of light erbium and ytterbium nuclei[2]. The analysis of the results is not yet completed. We wish, however to draw attention to one particular decay sequence, $^{154}Ho \xrightarrow{\beta} {}^{154}Dy$, which appears to offer interesting possibilities for the further study of levels in ^{154}Dy. Originally the nucleus ^{154}Dy was observed following the successive β decay of ^{154}Er, but for the present study ^{154}Ho was made directly by the reactions:

$$^{148}Sm(^{11}B,5n)^{154}Ho \xrightarrow{\beta} {}^{154}Dy; \quad \text{and}$$

$$^{148}Sm(^{10}B,4n)^{154}Ho \xrightarrow{\beta} {}^{154}Dy$$

To gain further insight into the level scheme of ^{154}Dy we have also studied the "in-beam" spectrum by the reaction: $^{139}La(^{19}F,4n)^{154}Dy$. No level scheme has previously been proposed for ^{154}Dy, although Lagarde et al.[3] have observed the β-decay of ^{154}Ho and place the 2^+ level at 335 keV; Morinaga and Gugelot[4]) have also studied the in-beam spectrum by a (^{4}He,4n) reaction, but only the $2^+ \rightarrow 0^+$ transition was assigned.

Since ^{154}Dy has 88 neutrons, it would be expected that the energy levels would be quite different from those of the heavier dysprosium nuclei, which are rotational in character. It is well known that the transition between vibrational and rotational behavior appears to occur abruptly between 88 and 90 neutrons in this region.

2. Experimental

The reactions (^{11}B,5n) and (^{10}B,4n) on ^{148}Sm were used to produce ^{154}Ho; the yield was found to peak at approximately 75 MeV bombarding energy for ^{11}B, and 60 MeV for ^{10}B. The spectra obtained were essentially identical. The heavy-ion beams were provided by the Hilac at Berkeley. Gamma rays were detected in a lithium-drifted germanium counter measuring 6 sq. cm × 1.3 cm. The pulses were analyzed by a 2048 channel ADC and stored using a PDP 7 computer on-line. The target consisted of a self-supporting foil of separated isotope and was approximately 700 μgms cm^{-2} in thickness. The half life of the β-decay was determined as 3.25 ± 0.1 minutes from measurement of the decay curves, and it was found convenient to maintain the pulsed beam of the Hilac on the target, whilst the ADC was gated to analyze pulses occuring between the beam bursts. Gamma-gamma coincidence experiments were also performed using the same technique. The counters were placed at 90° to the beam direction, and on opposite sides of the target. In one case we employed two germanium counters; however, to improve counting statistics on the high energy gamma rays, a second experiment using a NaI (3" × 3") and a germanium counter was also performed. A multi-dimensional computer program was used for these experiments; events were stored on magnetic tape and were sorted off-line. Chance coincidences were completely negligible in both the experiments.

The reaction: $^{139}La(^{19}F,4n)^{154}Dy$ was used to study the "in-beam" spectrum of ^{154}Dy. The lanthanum target was prepared by evaporation of natural lanthanum onto a lead foil of 0.05 mm thickness. Excitation functions were performed, and at the peak bombarding energy, 86 MeV, the anisotropies of the gamma rays were determined by measuring relative yields at 0° and 90° with respect to the beam direction. Further details of the experimental arrangement may be found in ref. [5]).

To characterise the sequence $^{154}Er \overset{\beta}{\rightarrow} {}^{154}Ho \overset{\beta}{\rightarrow} {}^{154}Dy$ we have also produced the nucleus ^{154}Er by the reaction: $^{148}Sm(^{12}C,6n)^{154}Er$ at 90 MeV. Gamma spectra of the activity in the target foil after bombardment were recorded at intervals in order to measure decay curves. The spectrum of γ rays in ^{154}Dy, and the half lives observed, were quite different from those observed when the ^{154}Ho was produced directly by the (HI,xn) reaction. We conclude therefore that there are two levels in ^{154}Ho which β-decay to ^{154}Dy. These measurements are discussed in section 5. Unless otherwise stated we refer to the 3.25-minute activity of ^{154}Ho in the following sections.

3. Results

The gamma spectrum associated with the β-decay of ^{154}Ho is shown in fig. 1. All the prominent lines have a half life of 3.25 minutes, within experimental errors, with the exception of the transition at 283.1 keV. A typical spectrum for ^{154}Dy produced "in-beam" is shown in fig. 2. Transitions between members of the ground state quasi-rotational band are indicated on the figure.

In table 1, the transitions from the β-decay were assigned to ^{154}Dy from consideration of their half life. In cases where the line was so weak it was not possible to determine its half life to better than ± 0.5 minutes, we have omitted it from the table. Transitions from the (^{19}F,4n) reaction were assigned from consideration of their excitation function. Included in this table are values for the anisotropies, which we have defined as: $(I_0-I_{90})/I_{90}$. Spin assignments considered reasonably certain are indicated by A in the last column, B denotes tentative spin assignment.

Counting statistics in the Ge-Ge coincidence spectra were not entirely satisfactory; however, analysis of this experiment showed that the transitions of the proposed ground state band were in coincidence with one another. We can also say that the 407.0-keV and 346.5 keV γ rays were in coincidence, and that the 570.keV γ ray was in coincidence with the 334.7-keV γ ray, but not with the 412.5-keV γ ray. Typical spectra are shown in fig. 3. The spectrum in fig. 3a was the result of sorting events in which the energy of the gamma ray detected in the "gate counter" was not restricted. In fig. 3b, the $2^+ \rightarrow 0^+$ transition arises entirely from the background lying underneath the peak of the $2^+ \rightarrow 0^+$ transition in the "gate counter." The yields of the other gamma rays have no significant contribution from this background. The same remarks apply to spectrum 3c with regard to the $4^+ \rightarrow 2^+$ transition, except in this case about 10% of the $2^+ \rightarrow 0^+$ arises from the background.

Information on the higher energy γ rays was provided by the NaI-Ge coincidences. Figure 4 gives the spectra in the germanium counter gated by various peaks in NaI spectrum. The background coincidence have been accounted for in an approximate way by subtracting the coincidence spectrum associated with an equal window in relatively flat portions of background ajacent to the peaks. Statistics on the points are therefore considerably poorer than indicated, and relative intensities should be regarded as a qualitative indication only. It is apparent however, that the 726.5 keV gamma ray feeds the band at the 8^+ level, whereas the 1249.5 keV gamma ray feeds in at the 6^+ level. The 815.0 keV gamma ray predominantly leads to the ground band at the 4^+ level, but several other transitions are enhanced.

4. The Level Scheme of ^{154}Dy

The ground state quasi-rotational band is established by the "in-beam" spectrum shown in fig. 2; the systematic spacings of the prominent lines and their relative intensities is convincing, in view of the considerable accumulation of data on similar reactions e.g., ref.[1]) and the references cited therein. Further evidence is provided by the anisotropies, which lie in the range 0.33-0.75 (table 1), consistent with a stretched E2 character[1]). Confirmation of the ground band up to the 8^+ assignment is provided by the coincidence data. This establishes a firm basis from which the position of other levels may be deduced by consideration of the energy sums and intensity balance. Since the transitions have been measured with a fairly good precision, the probability of chance agreements will not be high. We can then establish four additional levels as shown in fig. 5. These proposed levels, and their decays are confirmed by the coincidence data described in the previous section and shown in figs.

3 and 4. Most of the prominent lines are included in this scheme. Relative γ-ray intensities from the β-decay are indicated in fig. 5; the intensity balance is satisfactory if the β-decay were allowed to feed the levels at 1224.4, 1659.4, and 2474 keV. This, however, is not necessarily implied, since there could be sufficient intensity in the unassigned γ rays to balance the flow for the levels at 1659.4 or 1224.4 keV. However, it appears that a substantial fraction of the β-decay must feed the 2474-keV level.

5. Half Lives in the β-Decay Sequence $^{154}Er \rightarrow {}^{154}Ho \rightarrow {}^{154}Dy$

The results of the half life measurements are at first sight rather confusing. However the difficulties can be resolved once it is realized that for these neutron deficient systems, (HI,xn) reactions are no longer completely dominant. To explain the data we assume that charged particle reactions, especially (HI,pxn) have a significant yield. Thus when we used the reaction: $^{148}Sm(^{12}C,6n)^{154}Er$ there would be a considerable yield of ^{154}Ho by the p5n reaction[6]. This means that part of the ^{154}Dy yield would be due to direct β-decay of ^{154}Ho, in addition to that arising from successive β-decay of ^{154}Er.

The gamma spectrum of delayed activities after bombardment of the ^{148}Sm with ^{12}C at 90 MeV showed several prominent lines, and their decay curves indicated a half life of 5.8 ±0.3 minutes. We assign these transitions to ^{154}Ho populated by the β-decay of ^{154}Er in view of the close agreement between their half life and that measured for ^{154}Er by MacFarlane and Griffioen[7]. The $2^+ \rightarrow 0^+$, and $4^+ \rightarrow 2^+$ transitions assigned to ^{154}Dy were also present in this spectrum, and the decay curve for the $2^+ \rightarrow 0^+$ transition indicated that the half life of the daughter β-decay (^{154}Ho) was 11.8 ±0.5 minutes. However, there was a significant discrepancy between the measured decay curve and that calculated for the sequence A $\xrightarrow{5.8\text{ m.}}$ B $\xrightarrow{11.8\text{ m.}}$ C, where A and B were initially in equilibrium at a constant rate of production of A. In this spectrum the relative yield of the $4^+ \rightarrow 2^+$ transition (to the $2^+ \rightarrow 0^+$ transition) was much smaller than that measured for the decay of ^{154}Ho made directly by the HI reaction. Analysis of the decay curve for the $4^+ \rightarrow 2^+$ transition gave an initial half life of 3 ±1 minutes, however after about 20 minutes the curve was well represented by a half life of 11 ±2 minutes. At that time, the relative yield of the $4^+ \rightarrow 2^+$ transition was 15% (compared to 84% in fig. 1). It is therefore apparent that two levels in ^{154}Ho β-decay to ^{154}Dy. One level (populated in the (HI,xn) reaction to make ^{154}Ho) β-decays with $T_{1/2}$ = 3.25 minutes, feeding high spin levels in ^{154}Dy with 84% relative yield of the $4^+ \rightarrow 2^+$ transition (fig. 5): the other level (populated in the β-decay of ^{154}Er) β-decays with $T_{1/2}$ = 11.8 minutes, feeding low-spin levels in ^{154}Dy with 15% relative yield of the $4^+ \rightarrow 2^+$ transition. However, the behavior of both the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ decay curves can only be accounted for if we assume that about 30% of the initial activity of the $2^+ \rightarrow 0^+$ transition was due to β-decay of the 3.25 minutes activity in ^{154}Ho level <u>not</u> fed by the β-decay of ^{154}Er, but populated by the competing p5n reaction. The scheme is summarized in fig. 6. The level with $T_{1/2}$ = 11.8 minutes is almost certainly that recently observed by Hahn et al.[8]) from its α-decay with $T_{1/2}$ = 11.8 minutes. Clearly this level has a low spin, whereas the 3.25-minute level is of a high spin; however, which of these levels is the ground state of ^{154}Ho can not be decided from the present experiments. The results indicate that there was no detectable population of the 11.8-minute activity in ^{154}Ho following the (HI,xn) reaction.

This is in accord with expectations; the angular momentum of the ^{154}Ho would be rather high after the reaction, so that a level of high spin should receive more population than one of low spin if the levels are not too different in energy. (See Sect. 6 below).

6. Discussion

It is of interest to consider possible interpretations of the levels in ^{154}Dy which are not part of the ground band. The branches of the 906-keV level indicate that its spin is probably 2^+, and we might speculate that the levels 906.0, 1252.4, and 1659.4 keV form another collective sequence, possibly of spins $2^{+'}$, $4^{+'}$, and $6^{+'}$. These levels would then be part of a quasi β-band[9]), in analogy with the β-band which occurs in deformed nuclei. The transition at 406.8 keV is probably of a stretched E2 character as evidenced by its anisotropy[1]) (see table 1). The level scheme below 1 MeV is very similar to those of the other 88-neutron nuclei in this region, e.g. ^{150}Sm and ^{152}Gd[10]). These nuclei have, in addition, a $0^{+'}$ level below 1 MeV which is possibly the ground state of the quasi β-band. Such a level would have been very weakly populated in the present case, and its associated γ rays could have escaped detection.

The (^{19}F,4n) reaction led to very weak excitation of the proposed quasi β-band. This is understandable, since such reactions bring large amounts of angular momentum into the residual nucleus, and therefore the most heavily populated levels should be the yrast levels[11]). The fact that the ground-state rotational bands are always heavily populated in (HI,xn) reactions leading to deformed even nuclei is an illustration of this remark. It is possible to observe strong population of other bands i.e., levels which are not yrast levels, only if the angular momentum brought in is not large, such as could be achieved by using protons or alphas as the projectile, see e.g., ref. [12]).

The β-decay leads to a rather strong population of the 8^+ level (16%), which implies that the spin of the 3.25-minute level in ^{154}Ho is unusually high. The preference of the β-decay to populate the level at 2474 keV suggests that this level may be related to the 3.25 minute level of ^{154}Ho, in which case it might be expected that the level would be K-hindered in its decays to the collective levels. In the in-beam work on ^{154}Dy we did not detect any delayed population of the ground band, however the level at 2474 keV could only have been weakly populated, since its decays established by the β-decay study were not detected.

We feel that the β-decay of ^{154}Ho to ^{154}Dy offers a good opportunity to study collective levels in ^{154}Dy in some detail; rarely does β-decay populate levels of such high angular momentum in even nuclei. We intend to study the nature of the additional collective levels which have been proposed here from the spectrum of conversion electrons in the β-decay. Through such experiments it might be possible to detect a $0^{+'}$ level. Also, it would be important to establish whether the proposed transitions $J' \rightarrow J$ at 434.9, 505.2, and 570.6 keV have substational E0 components. This would be expected if the levels J' have characteristics of a K = 0 β-vibrational band.

Acknowledgments

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4) H. Morinaga, P. C. Gugelot, Nucl. Phys. 46 (1963) 210

5) For a general description see J. E. Clarkson, R. M. Diamond, F. S. Stephens, and I. Perlman, Nucl. Phys. A93 (1967) 272. Details of the angular distribution measurements are described in ref. [1]). The coincidence techniques are described in David Ward, R. M. Diamond, F. S. Stephens, to be published.

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11) By "yrast level" we mean the lowest-lying level of a given spin, viz. e.g. J. R. Grover, Phys. Rev. 157 (1967) 832

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Table 1

Gamma rays assigned to ^{154}Dy

Decay of ^{154}Ho $\xrightarrow{\beta}$ ^{154}Dy		^{139}La (^{19}F,4n) ^{154}Dy			Assignment	
Transition (Energy keV)	Relative Intensity	Transition (Energy keV)	Relative Intensity	Anisotropy		
157.8 ±0.2	3.9 ±0.3					
289.2 ±0.2	4.3 ±0.3					
295.8 ±0.2	12.8 ±0.5	295.8 ±0.3	7 ±2	-0.4 ±0.15		
310.3 ±0.25	3.0 ±0.3					
334.7 ±0.25	100	334.7 ±0.25	100	0.53 ±0.08	$2^+ \rightarrow 0^+$	A
346.5 ±0.3	12.5 ±1.0				$4^{+'} \rightarrow 2^{+'}$	B
407.0 ±0.3	24.5 ±1.0	406.8 ±0.4	9 ±3	0.8 ±0.3	$6^{+'} \rightarrow 4^{+'}$	B
412.5 ±0.3	84 ±4	412.5 ±0.3	100 ±5	0.6 ±0.1	$4^+ \rightarrow 2^+$	A
434.9 ±0.4	2.5 ±0.3				$6^{+'} \rightarrow 6^+$	B
		439.8 ±0.5	29 ±4	-0.36 ±0.1		
444.2 ±0.4	5.1 ±0.5					
		448.0 ±0.5	8 ±3	2.0 ±1		
471.9 ±0.6	2.5 ±0.4					
477.4 ±0.4	56 ±2	477.6 ±0.4	85 ±5	0.8 ±0.1	$6^+ \rightarrow 4^+$	A
		488.0 ±0.5	11 ±2	0.2 ±0.2		

Table 1 (Cont)

Decay of $^{154}Ho \xrightarrow{\beta} {}^{154}Dy$		$^{139}La\,(^{19}F,4n)\,^{154}Dy$			Assignment	
Transition (Energy keV)	Relative Intensity	Transition (Energy keV)	Relative Intensity	Anisotropy		
505.2 ±0.4	16.2 ±0.7				$4^{+'} \rightarrow 4^{+}$	B
523.8 ±0.4	16.0 ±0.7	524.1 ±0.4	73 ±5	0.7 ±0.1	$8^{+} \rightarrow 6^{+}$	A
		557.3 ±0.4	45 ±5	0.6 ±0.15	$10^{+} \rightarrow 8^{+}$	A
570.6 ±0.5	10 ±2				$2^{+'} \rightarrow 2^{+}$	B
		589.0 ±1	30 ±5	0.3 ±0.15		
		616.0 ±1	22 ±4	0.3 ±0.15		
		637.0 ±1	21 ±4	0.8 ±0.3		
726.5 ±0.7	13 ±2				$(7^{\pm},8^{+}) \rightarrow 8^{+}$	B
815 ±0.7	13 ±3				$(7^{\pm},8^{+}) \rightarrow 6^{+'}$	B
906 ±1	1.5 ±0.5				$2^{+'} \rightarrow 0^{+}$	B
1249.5 ±1	16 ±2				$(7^{\pm},8^{+}) \rightarrow 6^{+}$	B

Figure Captions

Fig. 1. Gamma spectrum of the decay $^{154}Ho \overset{\beta}{\rightarrow} {}^{154}Dy$ observed between beam bursts following the reaction $^{148}Sm(^{11}B,5n)^{154}Ho$ at 75 MeV.

Fig. 2. Gamma spectrum observed during the beam bursts in the reaction $^{139}La(^{19}F,4n)^{154}Dy$ at 86 MeV.

Fig. 3. Gamma-ray coincidence spectra of the decay $^{154}Ho \overset{\beta}{\rightarrow} {}^{154}Dy$ taken with two Li/Ge counters each measuring 6 sq. cms. × 1.3 cms.

Fig. 4. Gamma-ray coincidence spectra of the decay $^{154}Ho \overset{\beta}{\rightarrow} {}^{154}Dy$ taken in a Li/Ge counter gated by various peaks in a 3" × 3" NaI counter. Coincidences arising with the background underneath the peaks in the NaI counter have been approximately subtracted out. This procedure was not expected to be accurate, and the relative intensities of the transitions should be regarded as a qualitative indication only.

Fig. 5. Proposed level scheme of ^{154}Dy from the β-decay of the 3.25-minute level in ^{154}Ho (relative γ-ray intensities in parentheses) and from the reaction $^{139}La(^{19}F,4n)^{154}Dy$.

Fig. 6. Schematic representation of the β-decay sequence $^{154}Er \overset{\beta}{\rightarrow} {}^{154}Ho \overset{\beta}{\rightarrow} {}^{154}Dy$. The order of the levels in ^{154}Ho is not meant to be implied. The β-decay branches are intended to be a general indication of the predominant β- and γ-ray feeding.

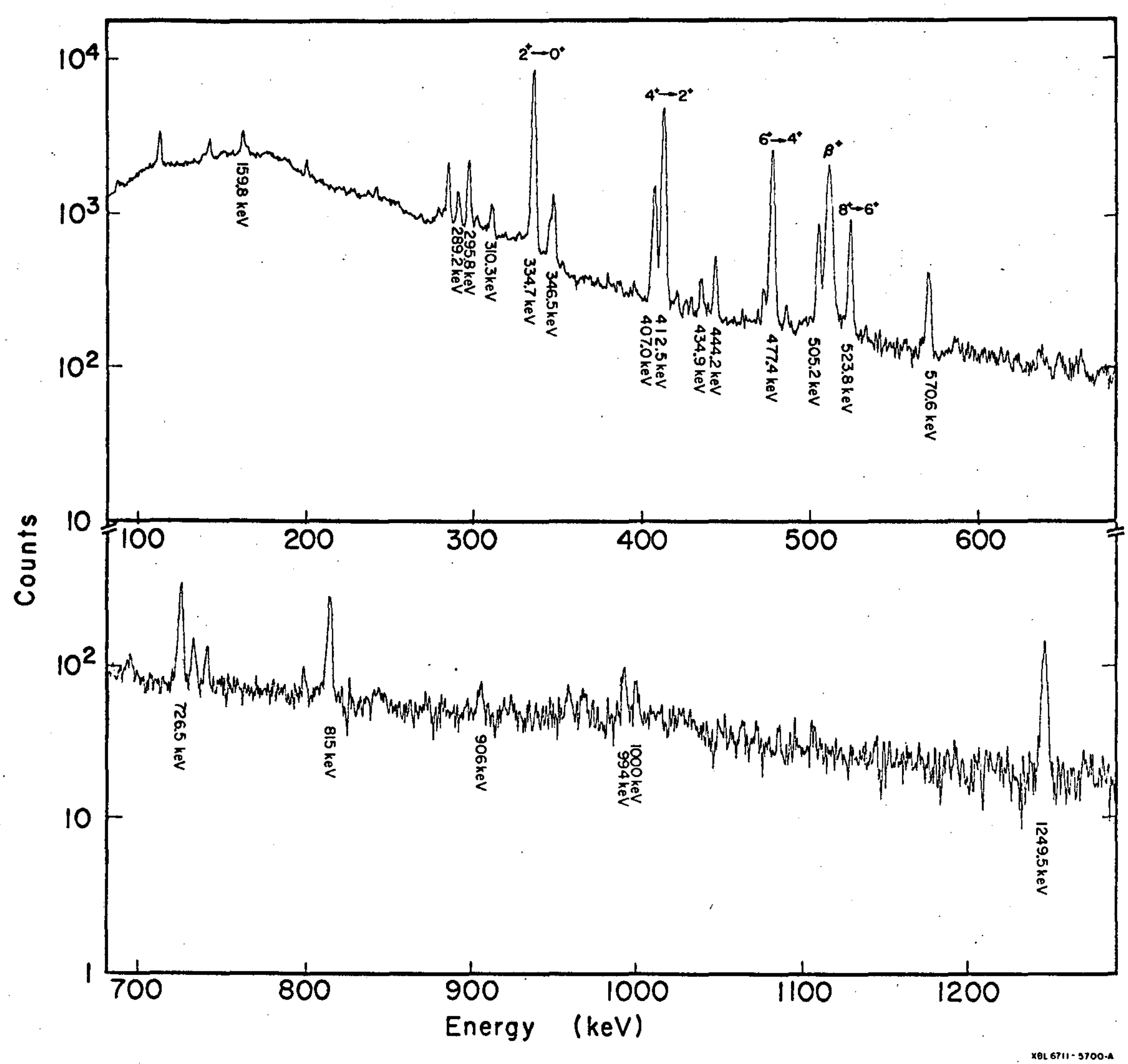
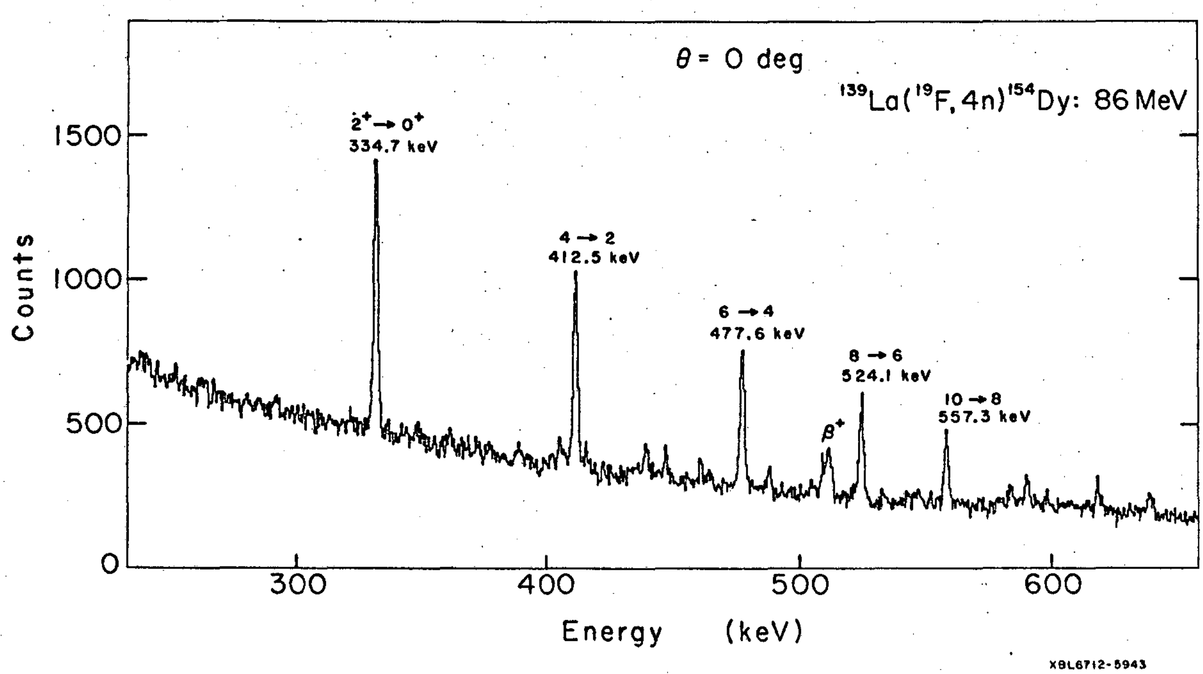

2+→0+
4+→2+
6+→4+
β+
8+→6+
159.8 keV
289.2 keV
295.8 keV
310.3 keV
334.7 keV
346.5 keV
407.0 keV
412.5 keV
434.9 keV
444.2 keV
477.4 keV
505.2 keV
523.8 keV
570.6 keV
726.5 keV
815 keV
906 keV
994 keV
1000 keV
1249.5 keV
Counts
Energy (keV)
XBL 6711-5700-A

Fig. 1



θ = 0 deg
139La(19F,4n)154Dy: 86 MeV
2+ → 0+
334.7 keV
4 → 2
412.5 keV
6 → 4
477.6 keV
8 → 6
524.1 keV
10 → 8
557.3 keV
β+
Counts
1500
1000
500
0
300
400
500
600
Energy (keV)
XBL6712-5943

Fig. 2

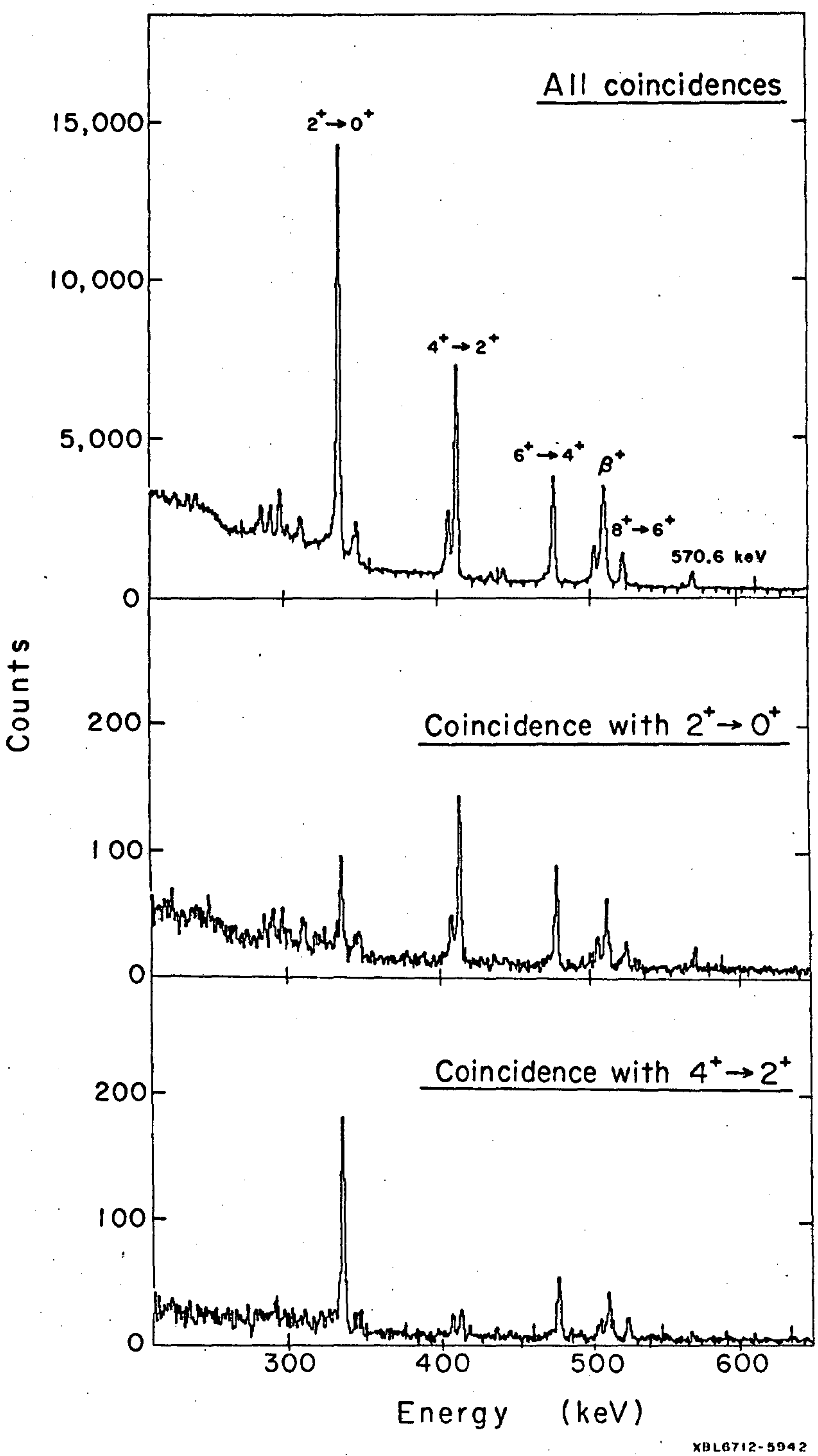
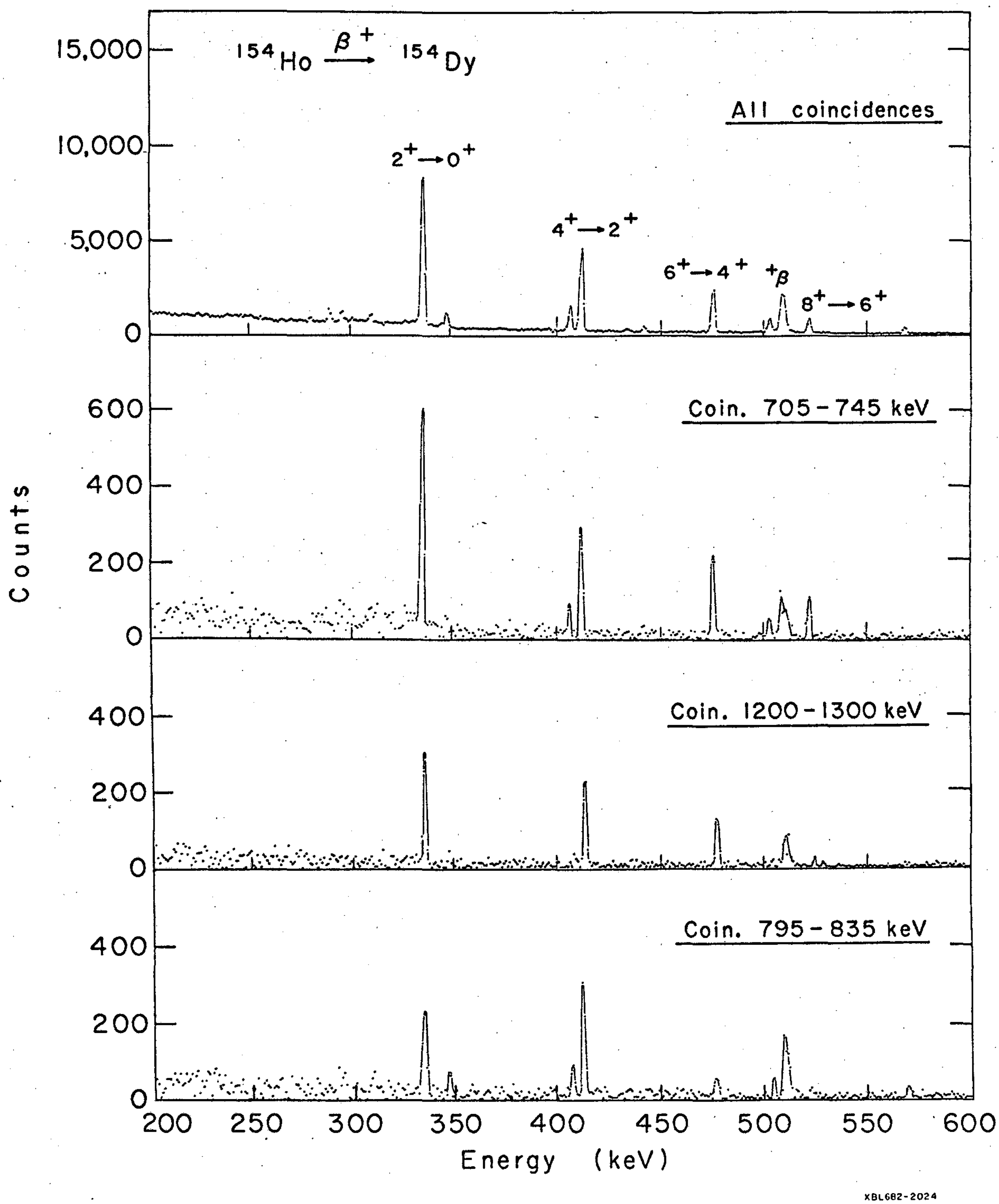

All coincidences
2+→0+
4+→2+
6+→4+
β+
8+→6+
570.6 keV
15,000
10,000
5,000
0
Counts
Coincidence with 2+→0+
200
100
0
Coincidence with 4+→2+
200
100
0
300
400
500
600
Energy (keV)
XBL6712-5942

Fig. 3



^{154}Ho $\xrightarrow{\beta^+}$ ^{154}Dy
All coincidences
$2^+ \to 0^+$
$4^+ \to 2^+$
$6^+ \to 4^+$
$+\beta$
$8^+ \to 6^+$
Coin. 705-745 keV
Coin. 1200-1300 keV
Coin. 795-835 keV
Counts
Energy (keV)
15,000
10,000
5,000
0
600
400
200
200 250 300 350 400 450 500 550 600
XBL682-2024

Fig. 4

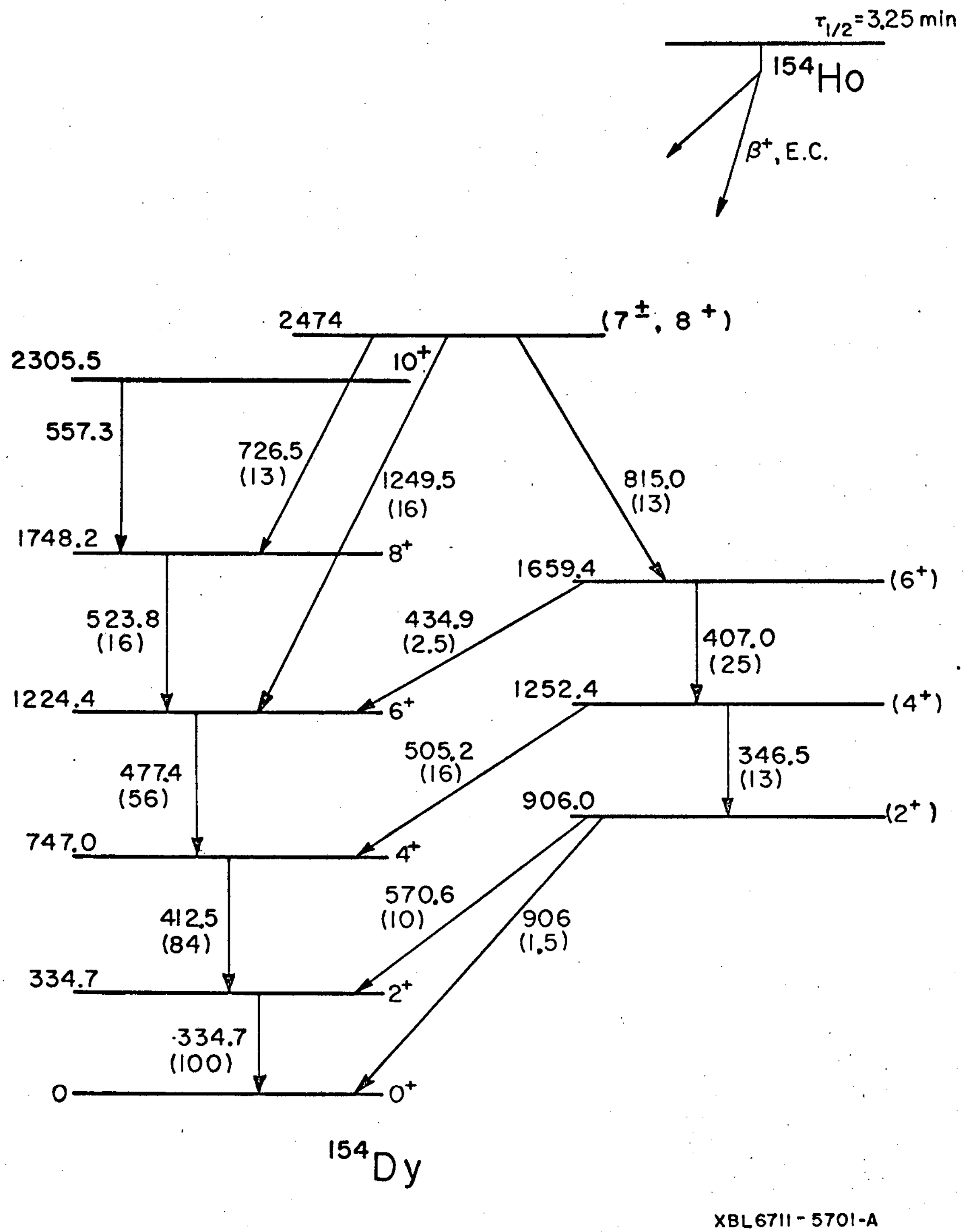

τ1/2=3.25 min
154Ho
β+, E.C.
2474
(7±, 8+)
2305.5
10+
557.3
726.5
(13)
1249.5
(16)
815.0
(13)
1748.2
8+
1659.4
(6+)
523.8
(16)
434.9
(2.5)
407.0
(25)
1224.4
6+
1252.4
(4+)
477.4
(56)
505.2
(16)
346.5
(13)
906.0
(2+)
747.0
4+
570.6
(10)
906
(1.5)
412.5
(84)
334.7
2+
334.7
(100)
0
0+
154Dy
XBL 6711-5701-A

Fig. 5

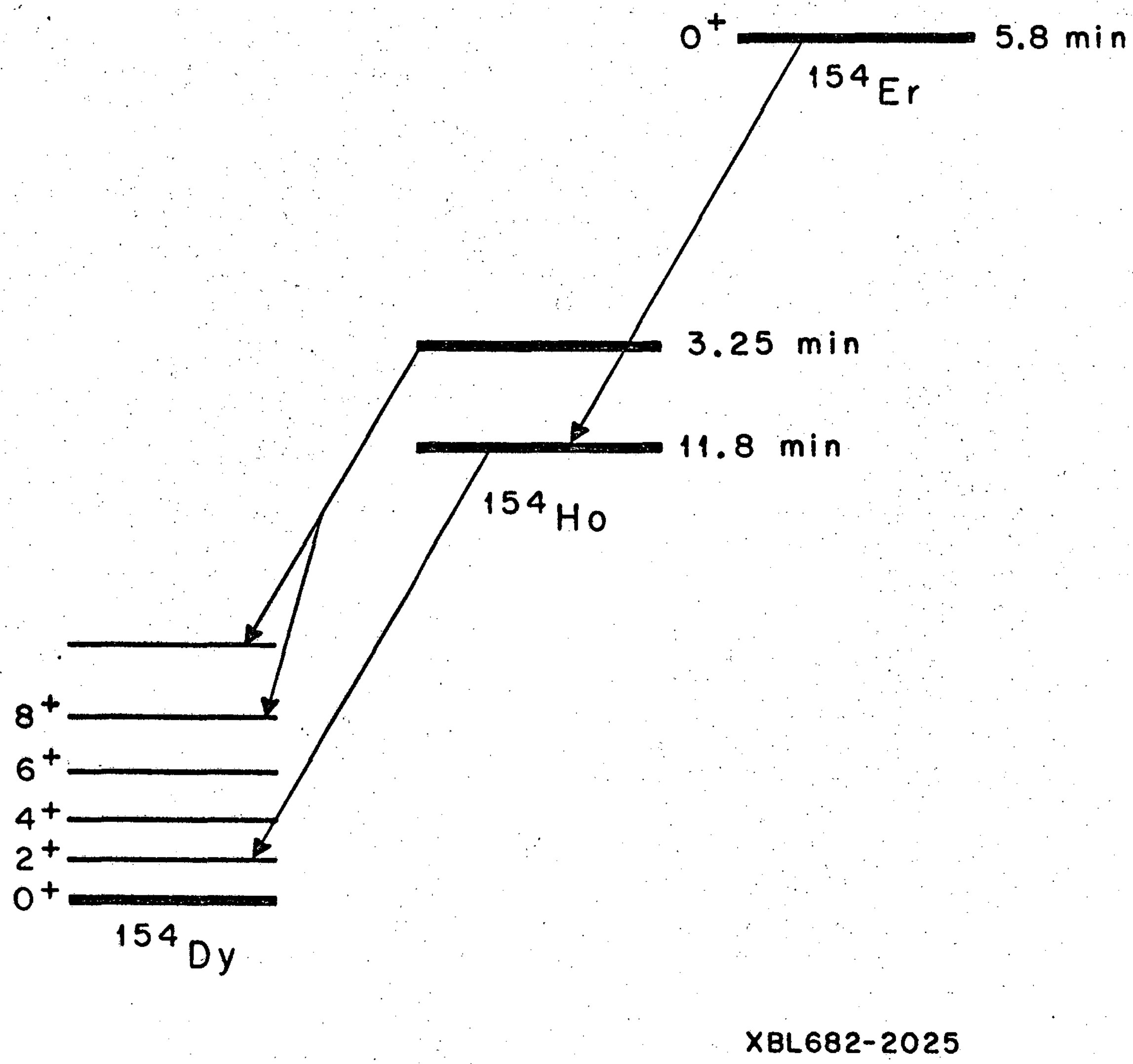


Fig. 6