August 1980

BNL 28226

CONF-8006119--1

Recent Experiments at Brookhaven: Level Structure of N = 86 Isotones ^{156}Yb and ^{150}Gd

by

A. W. Sunyar

Brookhaven National Laboratory, Upton, New York 11973 U. S. A.

MASTER

Invited Talk at Nobel Symposium 50, "Nuclei at Very High Spin - Sven Gösta Nilsson in Memoriam"

Örenäs, Sweden

June 23-27, 1980

Abstract

Recent experiments at Brookhaven: level structure of N = 86 isotones ^{156}Yb and ^{150}Gd. A. W. Sunyar (Department of Physics, Brookhaven National Laboratory, Upton, New York 11973 U. S. A.).
Physica Scripta (Sweden)

States of the N = 86 isotones ^{156}Yb and ^{150}Gd have been studied by means of the $^{144}Sm(^{16}O,4n)^{156}Yb$, $^{113}In(^{46}Ti,p2n)^{156}Yb$ and the $^{124}Sn(^{30}Si,4n)^{150}Gd$ reactions. Levels have been established to spin 36 ħ and over 12.5 MeV in excitation in ^{150}Gd and to beyond spin 25 ħ in ^{156}Yb. The systematics of levels in the N = 86 isotones from ^{150}Gd to ^{156}Yb are described, and the near-spherical shell model description for states in this region to near spin 30 ħ is discussed. A $T_{1/2}$ = 6 nsec, 72-keV isomeric transition in ^{156}Yb has been discovered, and an E1 multipolarity is assigned to this transition. The spin-parity of the isomeric state is established as 11^-.

Recent Experiments at Brookhaven:

Level Structure of N = 86 Isotones ^{156}Yb and ^{150}Gd

A. W. Sunyar
Brookhaven National Laboratory, Upton, New York 11973 USA

Early studies of the N = 86 nuclei ^{152}Dy[1] and ^{154}Er[2] resulted in identification of discrete states at very high spin, in the neighborhood of 38 ħ, at excitation energies which exceeded 12.5 MeV. Isomers were also observed[3] in this region, and lifetime measurements by Doppler shift techniques of several high spin states have been reported.[4] A great deal of experimental and theoretical effort has been expended in efforts to clarify the structure of these and other nuclei just above the magic N = 82 shell closure and the Z = 64 semi-magic subshell closure. Many structural features of these nuclei appear to arise from relatively simple single particle configurations in a near-spherical potential. The available shell model orbitals which play a major role in this region are illustrated in Fig. 1. In an effort to extend the available experimental information in this region with a view towards identification of systematic trends across the N = 86 isotones, studies of ^{150}Gd and ^{156}Yb have been initiated at the Brookhaven MP Tandem Facility. Preliminary results of this work will be presented here.

^{156}Yb has been investigated by means of the reactions ^{144}Sm(^{16}O,4n)^{156}Yb (E = 70-120 MeV) and ^{113}In(^{46}Ti,p2n)^{156}Yb (E = 190-210 MeV). The abundance of competing reactions necessitated the use of particle-gamma, K x-ray-gamma, as well as gamma-gamma coincidence experiments for identification of the transitions associated with ^{156}Yb. In addition, gamma-ray excitation functions, linear polarizations and angular distributions were measured in the course of these experiments. The resulting decay scheme is shown in Fig. 2, where assignments of spin and parity are considered firm up to the $J,\pi = 17^-$ state, From the 17^- to the 25^- state, some re-ordering may be necessary in the future because of difficulties associated with similar transition intensities.

Several interesting features emerge from an examination of the ^{156}Yb level scheme of Fig. 2.

(1) A marked similarity to the low-lying level sequence in ^{154}Er (see Fig. 2 of Ref. 2) is immediately apparent.

(2) An isomeric state exists in both nuclei at about the same spin and excitation energy.

(3) The population of the positive parity band (observed to only the probable 12+ state in ^{156}Yb) is considerably weaker ($< \sim 5\%$ of the main cascade) than in ^{154}Er, where the corresponding positive parity band is now known to spin 20.

(4) The 7^- and 9^- states observed in the decay of the 40 nsec isomer of ^{154}Er are not seen in the decay of the 6 nsec ^{156}Yb isomer.

(5) In contrast to the case of ^{154}Er, the isomeric transition in ^{156}Yb has been directly observed. This circumstance permits measurements (described below) which provide the basis for a rigorous spin and parity assignment of 11^- to the ^{156}Yb isomeric state and, by inference, to the ^{154}Er isomer as well.

(6) The energy spacing of the level sequence from the 11^- to 17^- states suggests a typical $(f_{7/2})^2$ neutron configuration built on

top of the 11^- isomer. This presumably terminates in the aligned neutron configuration $\left[(f_{7/2})^2_{6^+} \times (h_{9/2}, i_{13/2})_{11^-}\right]_{17^-}$. Above this configuration one may expect levels which can be described in terms of both proton and neutron excitations.

The series of measurements which determine the energy, half-life and multipolarity of the ^{156}Yb isomeric transition include:

(1) γ-γ coincidence measurements of low-energy electromagnetic radiation gated by clean high energy lines of ^{156}Yb to measure the energy and intensity of the isomeric transition.

(2) Time correlation measurements of γ-radiation relative to the pulsed beam.

(3) Gamma-ray angular distribution measurements relative to beam direction.

An example of a time correlation spectrum of γ-rays relative to beam pulse is shown in Fig. 3. A half-life of 6.0 ± 0.5 nsec for the isomeric state is derived from these data. The low-energy photon coincidence measurements show the presence of an intense 72-keV transition whose unconverted intensity fits well with that expected for an E1 transition ($\alpha_1 \simeq 0.94$) rather than with that expected for an M1 transition ($\beta_1 \simeq 10.7$). In addition, the W(θ) measurement for the 72-keV transition is consistent with that for a $\Delta J = -1$ transition feeding the known 10+ state with a mixing ratio $\delta \cong -0.1$. We thus conclude that the 6.0 nsec isomeric state has 11^- spin and parity and decays with a 72-keV predominantly E1 transition to the 10+ state. A probable dominant configuration for the 11^- state is the $\nu\left[h_{9/2}, i_{13/2}\right]_{11^-}$ aligned configuration.

A detailed comparison of ^{156}Yb and ^{154}Er levels which emphasizes the nearly identical nature of the spectra below the states with $J,\pi = 21^-$ is shown in Fig. 4. It may be remarked that 21^- is the maximum aligned spin-parity available from 4 neutrons beyond N = 82 in the shell-model space shown in Fig. 1.

The effective moments of inertia for these two N = 86 nuclei are quite similar above spin 15 with $\mathcal{J} \doteq 141$ MeV^{-1} for ^{156}Yb and 142 MeV^{-1} for ^{154}Er, a value some 13% in excess of the rigid sphere value.

Although we have emphasized similarities in the high spin level structure of these nuclei (at least to spin of the order of 21), the prospect for extending the comparison to very high spins is unfortunately limited. This results from a definite decrease in the population of high spin states above J = 25 in ^{156}Yb. While ^{154}Er states are strongly populated at high spin (60% of the ground state intensity at J = 25), the corresponding number for ^{156}Yb is only about 25%. As remarked earlier, a similar reduction in feeding of the positive parity band also occurs.

The N = 86 nucleus ^{150}Gd was studied by means of the ^{124}Sn(^{30}Si,4n)^{150}Gd reaction at 140 MeV. Experimental spectroscopic techniques similar to those mentioned earlier were used to establish the disintegration scheme. Fig. 5 shows the yrast states to spin 36 $\hbar$ and over 12.5 MeV in excitation energy deduced from our measurements. Previous work by Haenni et al. [5] had established the lower part of this scheme (below the 10^+ and 17^- states) by means of the (α,4n) reaction, and our results agree with their work. Other features of the scheme include:

(1) In contrast to ^{152}Dy, ^{154}Er and ^{156}Yb, no isomeric state with $T_{1/2} \geq 5$ nsec has been observed.

(2) Low-lying states ($J \leq 18$) exhibit a strong similarity to those in the other N = 86 even-even nuclei.

(3) The effective moment of inertia, obtained from the slope of the yrast energy vs. I(I+1) plot above the $I = 16^+$ state, is $\mathcal{J}_{eff} \doteq$ 140 MeV^{-1}, very close to the ^{152}Dy, ^{154}Er and ^{156}Yb values.

The systematics of the yrast energy-levels of N = 86 isotones from ^{150}Gd to ^{156}Yb are shown in Fig. 6. A number of trends are apparent in these data up to spin 17.

(1) The excitation energies of the 2+ to 8+ states decrease as Z increases.

(2) Low-lying negative parity states (3^- to 9^-) rise in excitation energy from Z = 64 to Z = 68 and are not observed in ^{156}Yb.

(3) A 10+ state occurs in close proximity to an 11^- state. These states are fed by cascades which extend to 16+ and 17^-, respectively, except for ^{156}Yb, where the positive parity cascade is not yet observed beyond 12^+.

An extension of the extreme single particle approach of Kleinheinz et al. [6] permits one to describe these features as due mainly to the neutron $(f_{7/2})^2$ or $(f_{7/2},h_{9/2})$ configurations coupled to the ground, the 3^- octupole phonon and to either the $(i_{13/2})^2_{10+}$ or the $(i_{13/2},h_{9/2})_{11^-}$ configurations. As mentioned earlier, states with spins exceeding about 20 $\hbar$ cannot arise from the maximal alignment of the 4 available valence neutrons and require contributions from the excitation of protons. It is interesting to note the existence of a band-like sequence of states starting with 21^- in ^{150}Gd and ^{152}Dy and 19^- in ^{154}Er. These sequences of decreasing energy quadrupole transitions closely resemble the 0,2,4,6+ energy spacings in the corresponding (N-2) isotopes (see Fig. 6). Such a correlation suggests an interpretation involving a stretched configuration of

$$\left[(\pi h_{11/2})^2_{10^+(8^+)} \times (h_{9/2}, i_{13/2})_{11^-}\right]_{21^-,(19^-)} \quad \text{as}$$

bandheads to which one couples the 0,2,4,6+ configurations to which the $(\nu f_{7/2})^2$ configuration is a major contributor. The recognizable features of such (j^2) configurations suggest that, in this region, relatively pure, near-spherical shell model states persist as a dominant excitation mode to high spins which approach 30 ħ.

Acknowledgements

The work reported here is a collaborative effort involving the dedicated efforts of my colleagues, C. Baktash, E. der Mateosian, O. C. Kistner, D. Horn and C. J. Lister. I am grateful to all of them for outstanding cooperation. This work is supported by the U. S. Department of Energy under Contract No. DE-AC02-76CH00016.

Department of Physics
Brookhaven National Laboratory
Upton, New York 11973
U. S. A.

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3. See, for example, Bjornholm, S., et al., in Proceedings of the Symposium on High Spin Phenomena in Nuclei, Argonne, Illinois, March 1979, p. 421.
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Figure Captions

Fig. 1. Shell-model valence orbitals for neutrons and protons above $N = 82$ and $Z = 64$, respectively.

Fig. 2. Level scheme for ^{156}Yb. Spin-parity assignments are firm to the 17^- state and tentative as to ordering above this spin.

Fig. 3. TAC spectrum of γ-ray events in a Ge-Li detector in coincidence with the pulsed beam.

Fig. 4. Low-lying level structure comparison of the $N = 86$ nuclei ^{154}Er and ^{156}Yb. Δ denotes the small unmeasured energy of the 11^- to 9^- ^{154}Er isomeric transition.

Fig. 5. Level scheme for ^{150}Gd.

Fig. 6. Systematics of yrast energy levels of $N = 86$ isotones ^{150}Gd, ^{152}Dy, ^{154}Er and ^{156}Yb. The dots adjacent to the 21^- to 27^- states in ^{150}Gd, ^{152}Dy and to the 19^- to 25^- states in ^{154}Er indicate the 0+ to 6+ level energies in the (N-2) isotopes relative to the 21^- (19^-) states as bandheads.

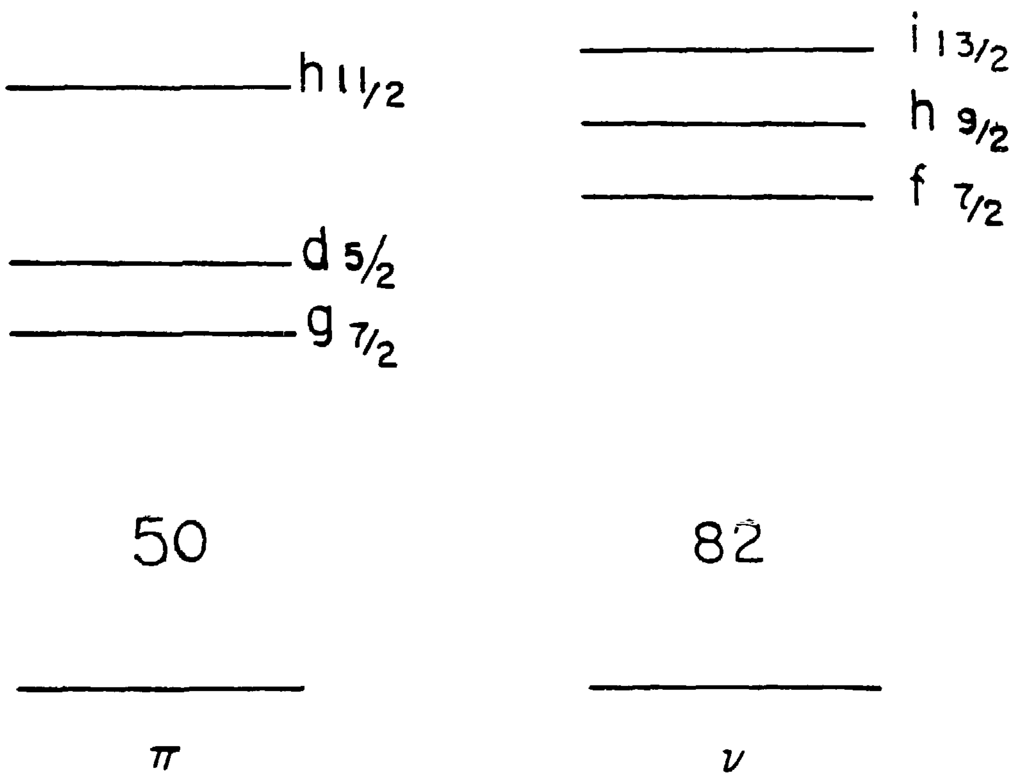
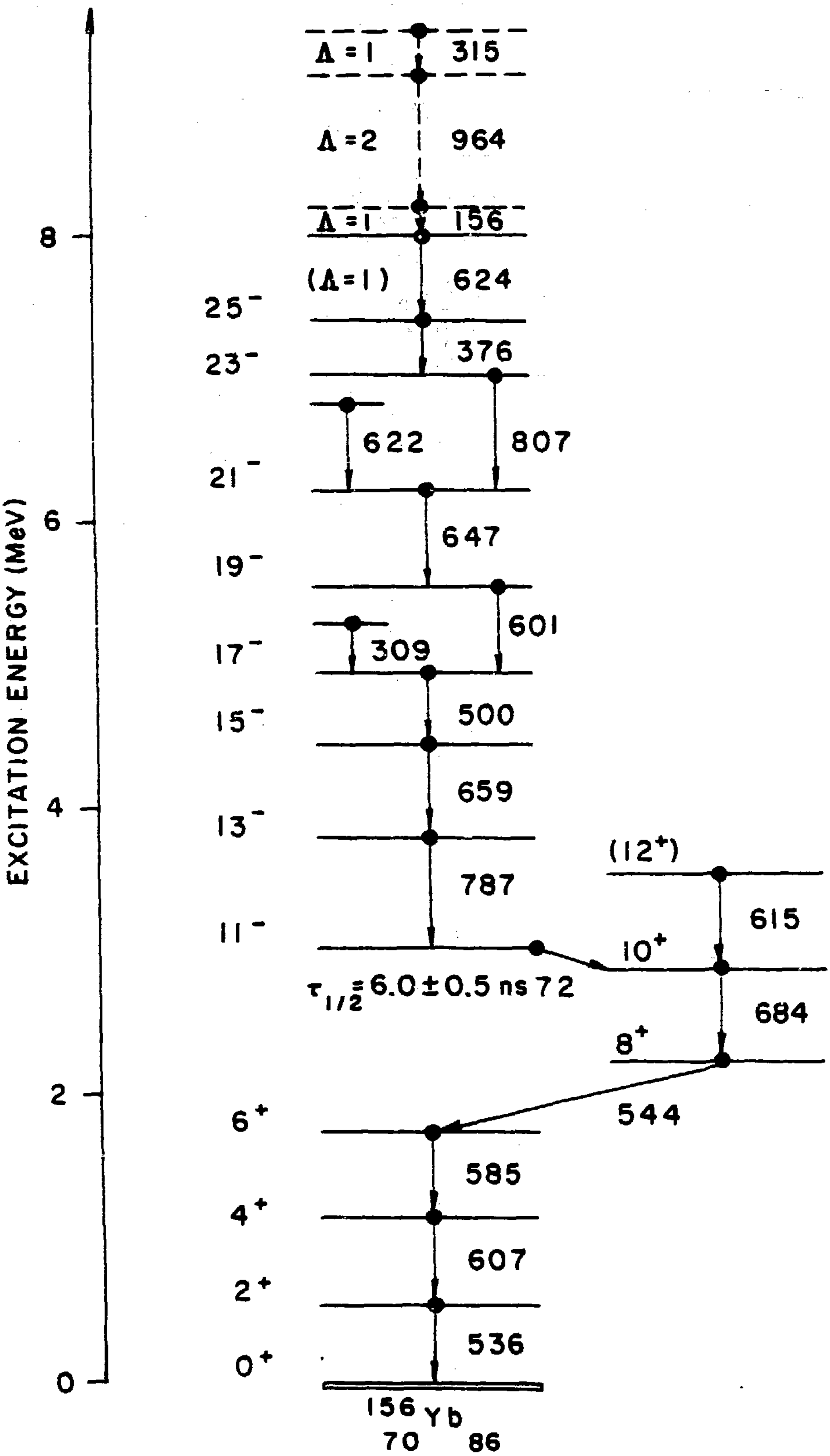
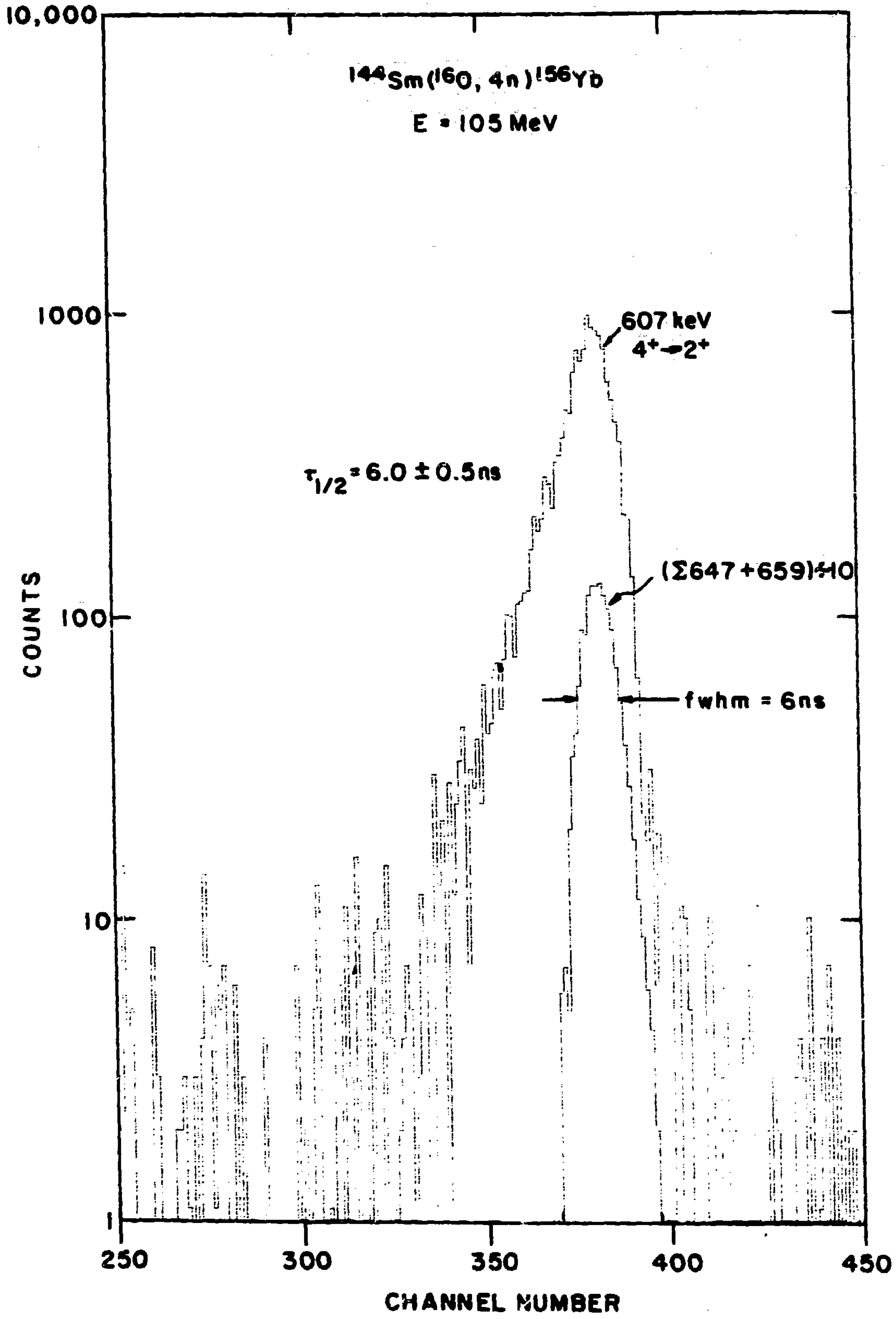


Figure 1



EXCITATION ENERGY (MeV)
8
6
4
2
0
Λ=1
315
Λ=2
964
Λ=1
156
(Λ=1)
624
25⁻
23⁻
376
622
807
21⁻
647
19⁻
601
17⁻
309
500
15⁻
659
13⁻
787
(12⁺)
615
11⁻
10⁺
τ1/2=6.0±0.5 ns 72
684
8⁺
544
6⁺
585
4⁺
607
2⁺
536
0⁺
156 Yb 70 86

Figure 2



10,000
1000
100
10
1
COUNTS
$^{144}Sm(^{16}O, 4n)^{156}Yb$
E = 105 MeV
607 keV
$4^+ \to 2^+$
$\tau_{1/2} = 6.0 \pm 0.5$ ns
(Σ647 + 659)÷10
fwhm = 6ns
250
300
350
400
450
CHANNEL NUMBER

Figure 3

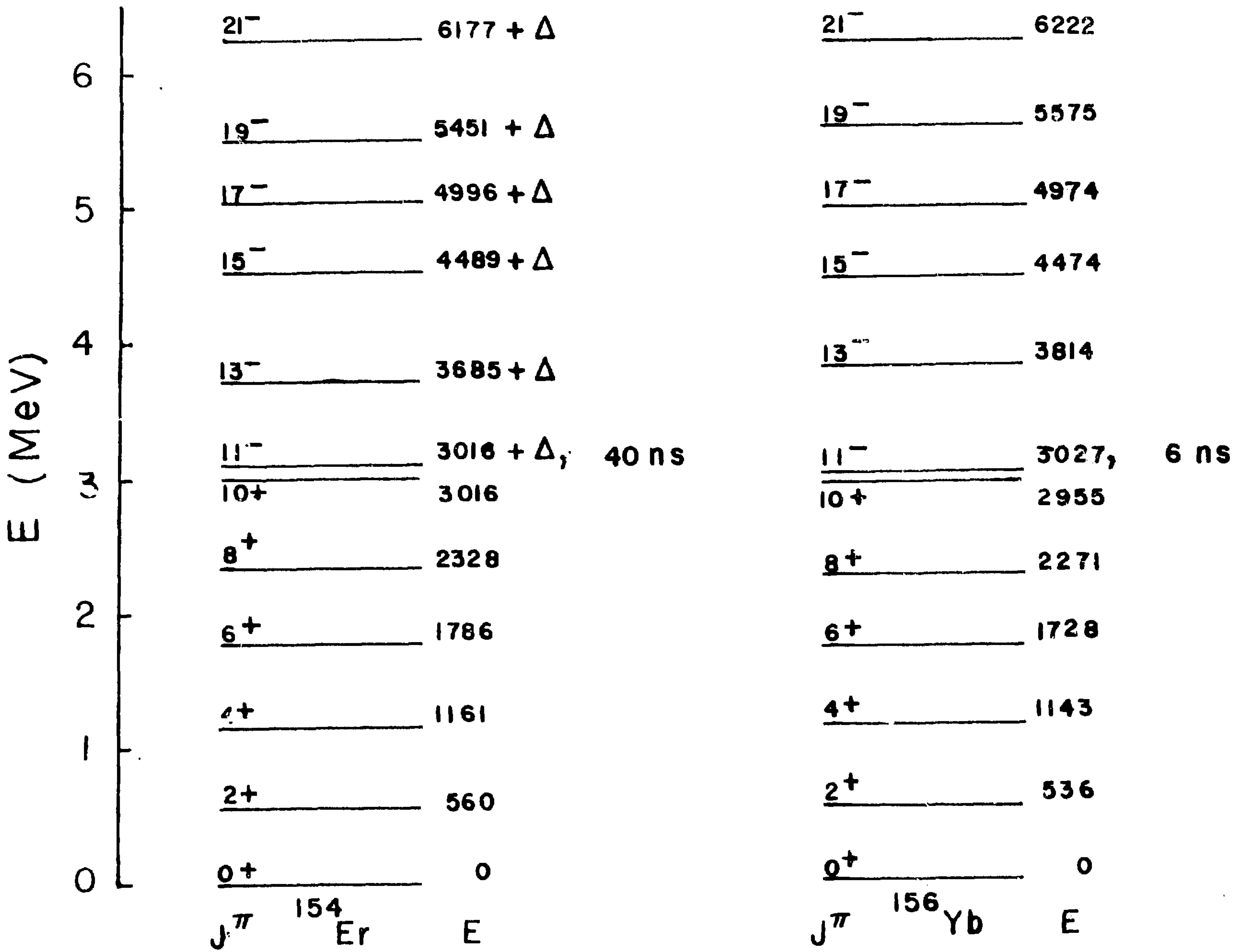

E (MeV)
0
1
2
3
4
5
6
21⁻ 6177 + Δ
19⁻ 5451 + Δ
17⁻ 4996 + Δ
15⁻ 4489 + Δ
13⁻ 3685 + Δ
11⁻ 3016 + Δ, 40 ns
10+ 3016
8+ 2328
6+ 1786
4+ 1161
2+ 560
0+ 0
J^{π} ^{154}Er E
21⁻ 6222
19⁻ 5575
17⁻ 4974
15⁻ 4474
13⁻ 3814
11⁻ 3027, 6 ns
10+ 2955
8+ 2271
6+ 1728
4+ 1143
2+ 536
0+ 0
J^{π} ^{156}Yb E

Figure 4

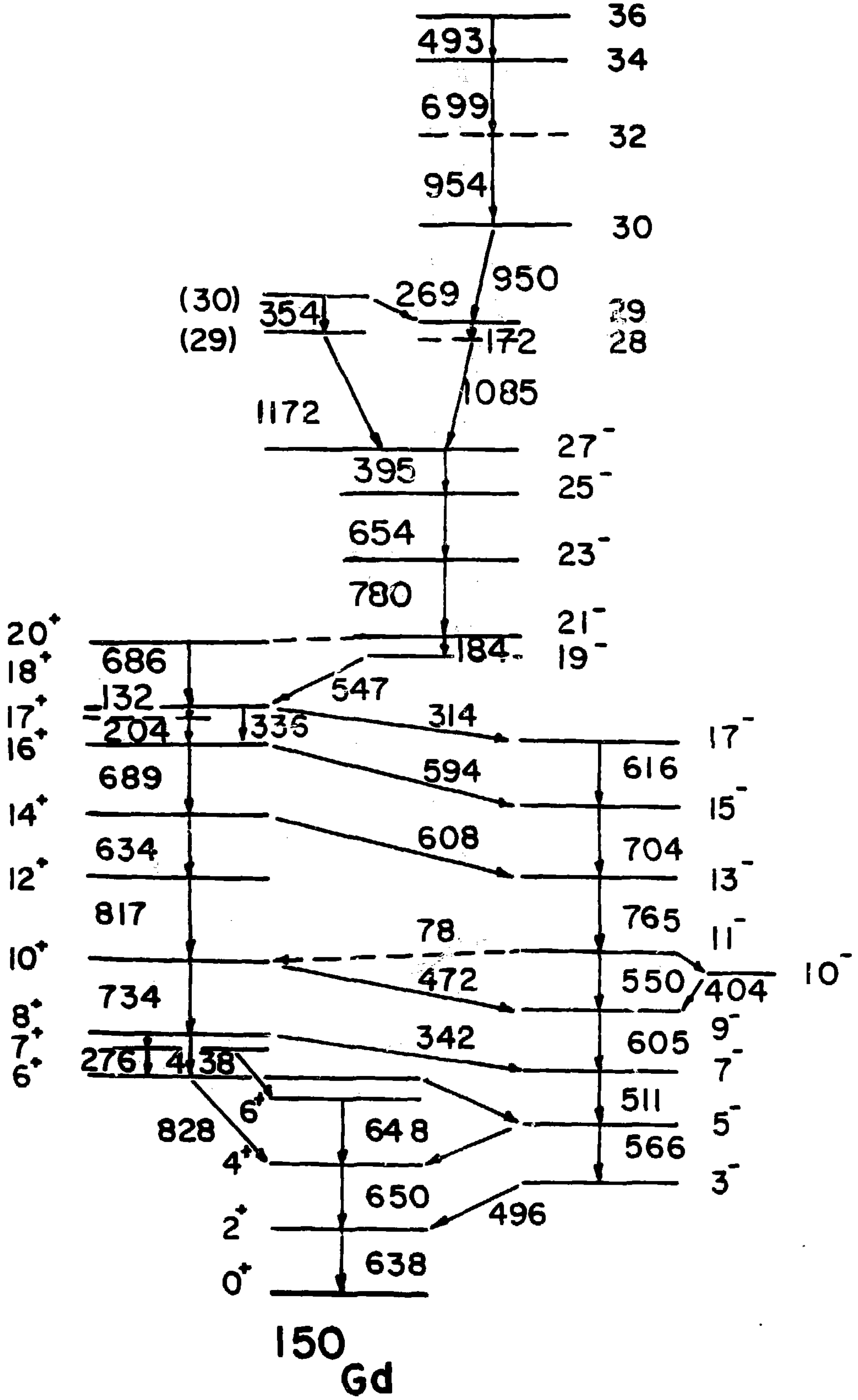
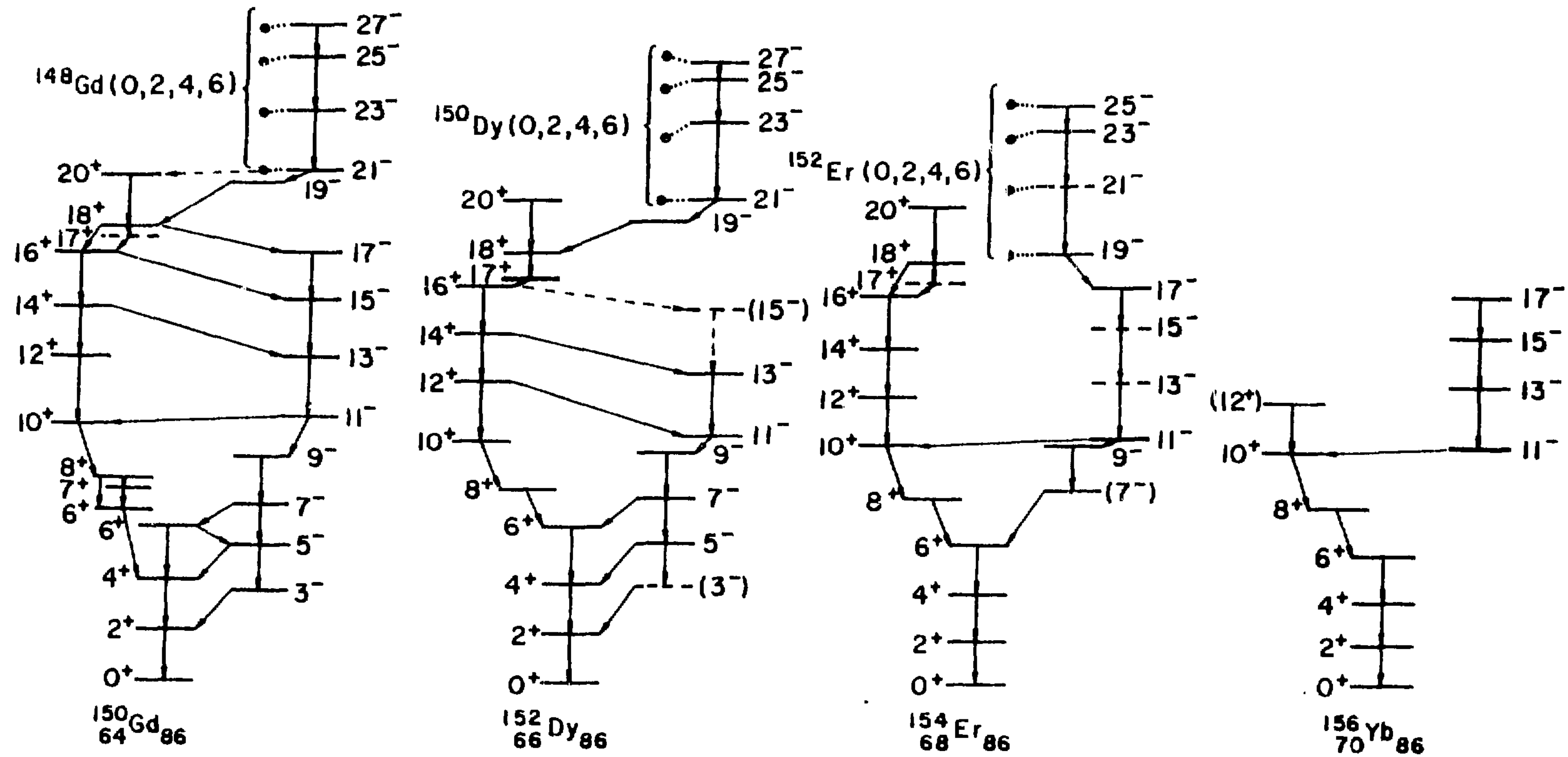

36
493
34
699
32
954
30
950
269
(30)
354
29
(29)
172
28
1085
1172
27⁻
395
25⁻
654
23⁻
780
21⁻
20⁺
686
184
19⁻
18⁺
547
132
17⁺
335
314
204
17⁻
16⁺
594
689
616
14⁺
15⁻
634
608
704
12⁺
13⁻
817
765
78
11⁻
10⁺
10⁻
734
472
550
404
8⁺
9⁻
7⁺
342
605
6⁺
276
438
7⁻
511
6⁺
648
5⁻
828
566
4⁺
650
3⁻
2⁺
496
638
0⁺
150
Gd

Figure 5



148Gd(0,2,4,6)
150Dy(0,2,4,6)
152Er(0,2,4,6)
150 64 Gd 86
152 66 Dy 86
154 68 Er 86
156 70 Yb 86

Figure 6