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Major professor

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ROTATIONAL BANDS IN ^{182}RE

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ABSTRACT

ROTATIONAL BANDS IN ^{182}RE

By

Mark Franklin Slaughter

Levels of the odd-odd deformed nucleus ^{182}Re were studied using the techniques of in-beam γ-ray spectroscopy. γ-singles, γ-γ coincidence, γ-ray angular distribution, and lifetime experiments were performed using Ge(Li) detectors.

Additional levels of the two previously reported rotational bands were observed. The bandhead of the upper band, assigned to the $9^-\{9/2^-[514\uparrow] \otimes 9/2^+[624\uparrow]\}$ configuration, was found to be delayed by 6 ± 2 nsecs. The 14^- and 15^- levels of this band are fed by transitions deexciting an isomeric level ($T_{1/2}$ = 88 ± 8 nsecs) at 2256.4 keV. From branching ratios obtained for the 7^+ band, together with the recently measured g-factor of the 64 hr isomer of ^{182}Re, the value of g_R for ^{182}Re was inferred to be 0.15 ± 0.07.

Members of two other rotational bands were identified. The first is thought to be built on the 2^+ 12.7 hr isomer while the second, built on an isomeric level ($T_{1/2}$ = 780 ± 90 nsecs), decays via the 461.3 keV transition to the 2^+ isomer.

ACKNOWLEDGEMENTS

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Finally, I especially wish to thank my advisor, Dr. W. H. Kelly, for suggesting this project, and for his interest, support, friendship, and, last but not least, patience over the past few years.

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INTRODUCTION

A fundamental goal of nuclear physics is to quantitatively characterize the nuclear force. This requires an understanding of the interactions of nucleons derived from nucleon-nucleon scattering experiments and nuclear structure studies. Nuclear structure, in particular, has been partially understood in terms of the nuclear shell model, which in its simplest form, considers each nucleon to move independently in the average potential created by the others. This is only an approximation to the actual situation. To further the agreement with experiment "residual interactions" are included as perturbations. Among these is the p-n residual interaction.

Odd-odd nuclei are particularly suited to a study of the p-n residual interaction because of the large number of low-lying many-quasiparticle levels. Deformed odd-odd nuclei are of particular interest; however for experimental reasons these have been studied the least. Intrinsic states in deformed nuclei have been successfully predicted by the Nilsson model which treats nucleons as moving in a non-spherical potential. Single-particle states in the Nilsson model are characterized by the asymptotic quantum numbers $\Omega\Pi[Nn_z\Lambda\Sigma]$ where N and n_z are harmonic oscillator quantum numbers and Λ, Σ, and Ω are the projections on the nuclear symmetry axis of the particle orbital, spin, and total angular momenta, respectively (Ma 70). Π is the parity. In a deformed nucleus, levels due to the collective rotational motion of the nucleons also arise. For odd-odd nuclei these constitude rotational bands built on intrinsic several-quasiparticle states. The lowest level of each band, called the bandhead, is characterized by $I=K=\Omega$ where I is the total nuclear angular momentum and K is the projection of I on the nuclear symmetry axis. For axially symmetric nuclei K is a constant, to first order, throughout a given rotational band. If there is no significant mixing the rotational levels of a band can be fitted to the emperical expression.

$$E_{rot} = AI(I+1) + BI^2(I+1)^2$$

The constant A is $h^2/2\mathcal{I}$ where $\mathcal{I}$ is the nuclear moment of inertia (Sh 74).

This thesis reports the results of a γ-ray spectroscopic study of levels in the odd-odd nucleus ^{182}Re populated in-beam by the (α,3nγ) reaction. Prior to this work Hjorth et al. (Hj 68) proposed two rotational bands based on γ-ray singles and γ-ray angular distribution data taken with a Ge(Li) detector. Each band had six levels. K values of 7 and 4 or 5 were assigned. On the basis of γ-ray singles and γ-γ coincidence data taken with Ge(Li) detectors, Medsker et al. (Me 71) reported that the ordering of these bands was opposite to that proposed by Hjorth et al. A $7^+\{5/2^+[402\uparrow] \otimes 9/2^+[624\uparrow]\}$ assignment for the ground band and a $9^-\{9/2^-[514\uparrow] \otimes 9/2^+[624\uparrow]\}$ assignment for the upper band were suggested.

EXPERIMENTS

According to the Nilsson model ^{182}Re has a ground state spin and parity of 7^+ resulting from the triplet coupling of the $5/2^+[402\uparrow]$ proton and the $9/2^+[624\uparrow]$ neutron. This ground state has not been observed in decay studies. The 0^+ ground state of ^{182}Os β^+-decays to low spin states in ^{182}Re which feed the 2^+, 12.7 hr isomer. This isomer, which has been assigned to the singlet coupling $\{5/2^+[402\uparrow] \otimes 9/2^+[624\uparrow]\}$ (Bu 73) then decays directly to states in ^{182}W (Sc 75). Therefore a γ-ray spectroscopic study of high spin states in ^{182}Re must rely on in-beam techniques. The α-particle beam of the Michigan State University cyclotron is suited for this work. For medium mass nuclei bombarded with α beams of approximately 30 meV the (α, xnγ) reaction dominates. The number of neutrons which are "boiled off" depends on the incident beam energy. The nature of this compound nuclear reaction favors the population of a variety of high-spin states which decay to ground along the so-called yrast line. A typical γ-ray deexcitation scheme is shown in Figure 1 (Ne 70). Among any set of states at a particular excitation energy, the state with the highest K value will tend to be the most strongly populated. A large number of isomeric levels are expected to occur because the decay of high K levels to lower levels of much smaller K is forbidden (Ma 70). Instead these states must often decay directly to ground and are

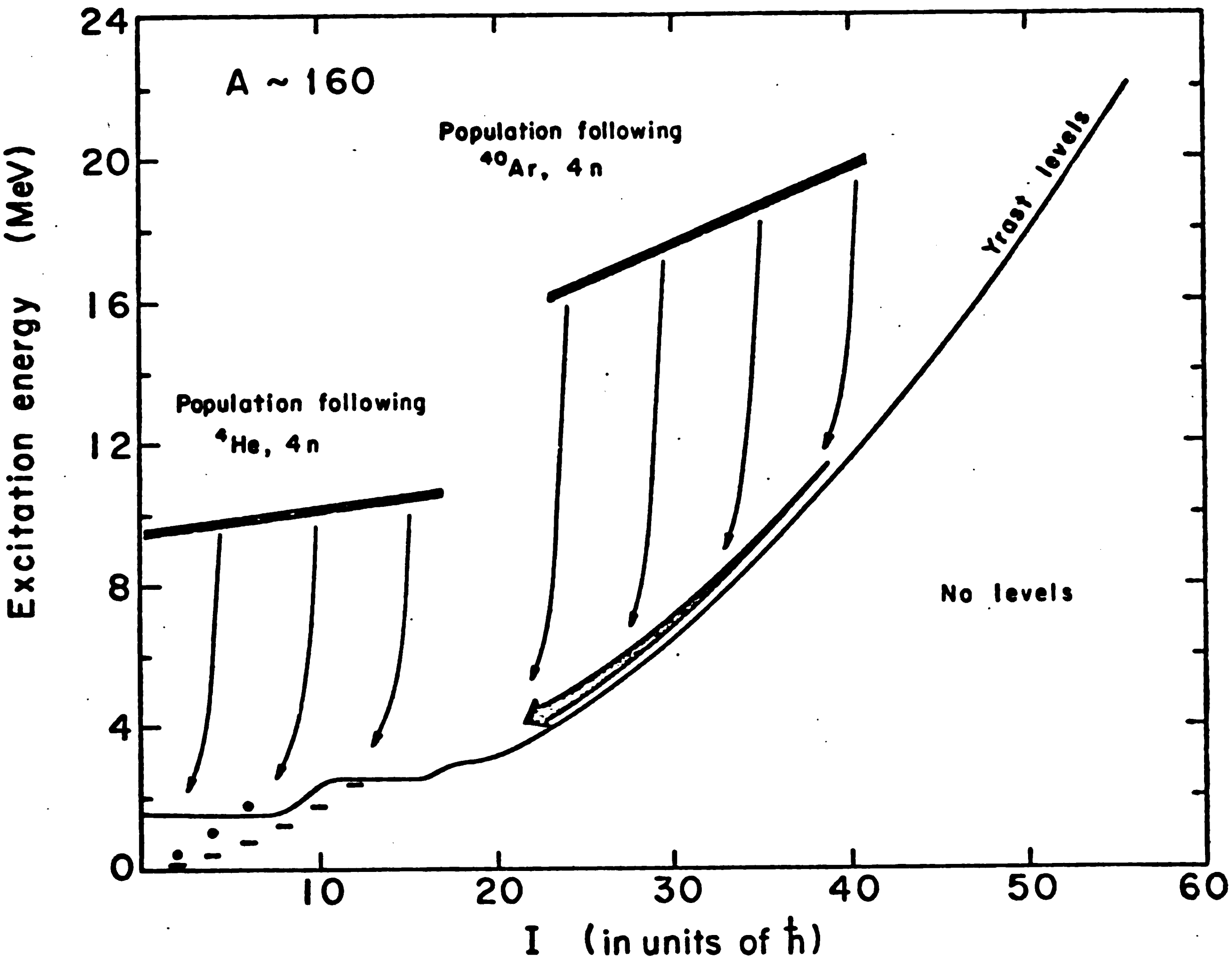

Figure 1. Schematic figure showing the energy levels in a nucleus of mass ∿ 160 versus angular momentum. Indicated on the figure are (i) the lowest non-g.s.b. energy levels for each spin (yrast levels), (ii) the regions of populated states following (He,4n) and (Ar,4n) reactions, and (iii) the g.s.b. levels of a typical vibrator (dots and rotor (dashes).

hindered with respect to transition rates based on the Weisskopf estimates (Le 67).

For this study the α particle beam of the MSU cyclotron was used to perform the (α,3 nγ) reaction on a 0.1 mil self-supporting ^{181}Ta foil. A rough excitation function established that the optimum beam energy for this reaction is 38 MeV. Singles data were taken with a Low Energy Photon (LEPs) Ge(Li) detector with a resolution of 650 eV at 122 keV. The detector was oriented at 125^{o} relative to the beam direction. This orientation reduces effects due to the angular distribution of the γ-rays (by rendering the term in $A_2 = 0$ - see page 5) and permits accurate evaluation of γ-ray peak intensities. Data were taken for γ-rays of energy up to 1 MeV. The resulting singles spectrum is shown in Figure 2. Table 1 lists γ-rays associated with the ^{181}Ta(α,3nγ)^{182}Re reaction with intensities evaluated from these data. Unless otherwise noted only γ-rays seen in coincidence with assigned transitions are included.

Three parameter (γ energy-γ energy-γ timing) coincidence data were taken with two true coax Ge(Li) detectors. Detector efficiencies were 4.5% and 7% relative to a 3" x 3" Na(Tl) detector for gammas at 1333 keV with a source to detector distance of 25 cm. Absorbers of about 12 mils each of Cu and Cd foil were placed in front of the detectors to minimize the contribution of X-rays to the count rate. Nine magnetic tapes of coincidence data, each

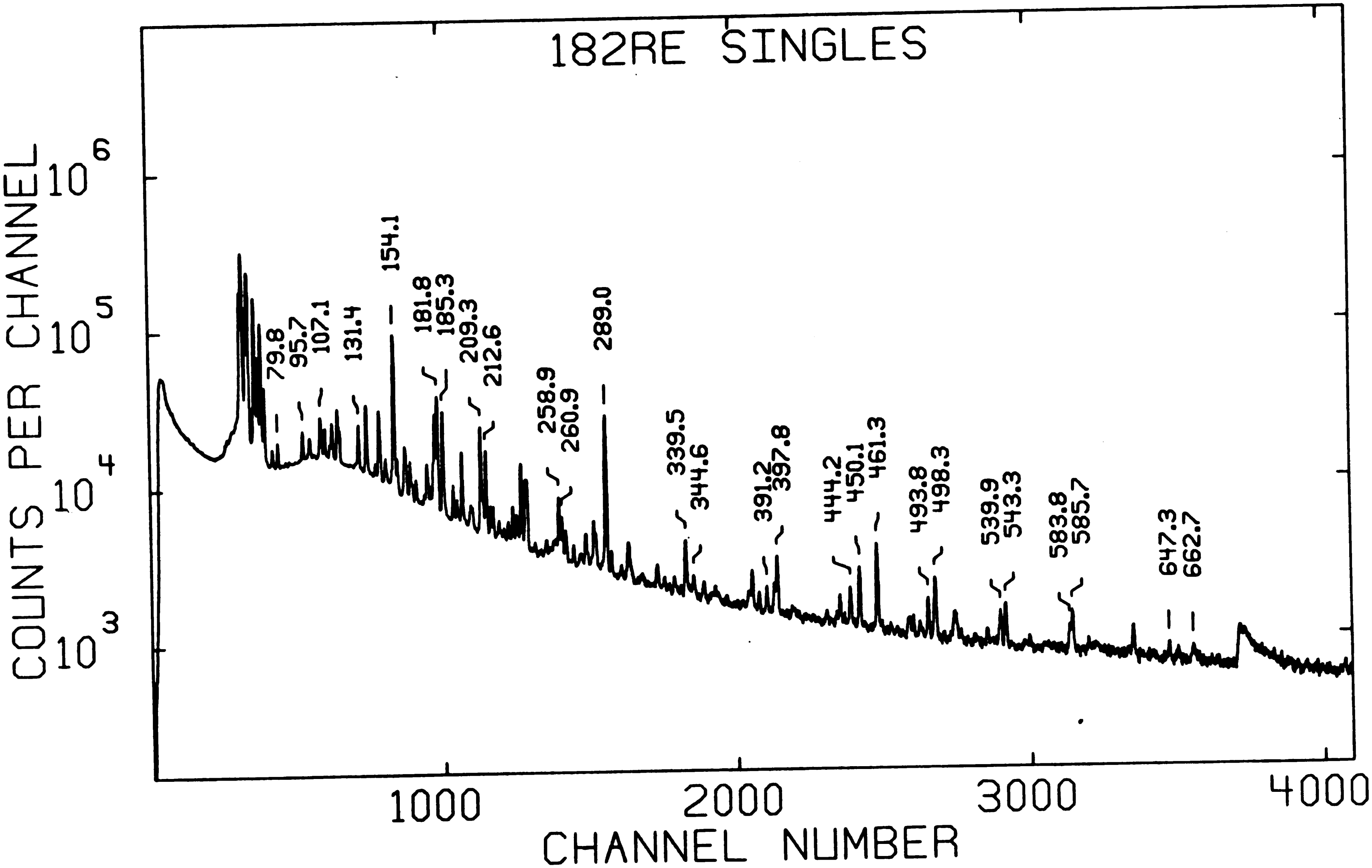

Figure 2. γ-ray singles taken with the LEPS detector.

TABLE 1

γ-RAYS OBSERVED IN-BEAM FROM THE ^{181}TA(α,3nγ)^{182}RE REACTION

Energy (keV)[a]	Intensity[b]	Energy (keV)[a]	Intensity[b]
55.6[c]	27	217.0	4.3 (0.5)
76.3	2.4 (0.2)	220.8	2.5 (0.3)
79.8	3.4 (0.2)	230.1 (0.3)[e]	---
95.7	4.2 (0.3)	231.8	5.5 (0.3)
107.1[d]	7.9 (0.5)	234.9	23 (1)
119.5	5.3 (0.3)	237.6	16 (1)
131.4	8.8 (0.2)	258.9	15 (1)
136.4[d]	17 (1)	260.9	8.9 (0.5)
152.3 (0.2)	1.6 (0.4)	263.3	6.3 (0.4)
154.1	80 (5)	268.0	3.2 (0.2)
160.4 (0.2)	11.7 (0.7)	276.0[e]	6.1 (0.4)
161.3 (0.2)		281.2 (0.2)	11 (1)
175.1[e]	8 (1)	282.3 (0.2)	6 (1)
179.3	8 (1)	289.0	100
180.2[f]	31 (2)	292.2	4.4 (0.3)
181.8	43 (3)	303.0	6 (1)
185.3	36 (2)	303.6	4 (1)
191.6[e]	6.3 (0.4)	321.3	4.2 (0.3)
197.2[e]	18 (1)	332.3	2.5 (0.2)
209.3	37 (2)	339.5[d,e]	14 (1)
210.6	5.5 (0.3)	341.7	1.8 (0.2)
212.6	23 (2)	344.6	3.4 (0.3)

Table 1--Continued

Energy (keV)[a]	Intensity[b]	Energy (keV)[a]	Intensity[b]
358.2 (0.2)	1.5 (0.2)	498.3[d]	21 (1)
391.2	5.1 (0.3)	539.9	8.4 (0.5)
395.9	6.4 (0.4)	543.3	13 (1)
397.8	17 (1)	583.8	6.9 (0.5)
437.6	6.5 (0.4)	585.7	13 (0.8)
442.2	9.2 (0.6)	624.5	9 (1)
450.1	18 (1)	647.3	4.9 (0.4)
461.3	33 (2)	662.7	3.6 (0.3)
493.8	11 (1)		

[a]Unless otherwise indicated, the uncertainty is $\pm$ 0.1 keV.

[b]Intensities are normalized to that of the 289.0 keV γ-ray.

[c]For experimental reasons this transition is not seen in this study. It is placed by Burson, et al (Bu 73).

[d]This peak is an unresolved multiplet of ^{182}Re γ-rays.

[e]This peak is an unresolved multiplet. Other com- coments (not belonging to ^{182}Re) are due to transitions in nuclei produced by the competing reactions.

[f]The $2^- \rightarrow 3^+$ transition is placed by Burson, et al. (Bu 73). (Not shown in the level scheme of Figure 9.)

containing about three million events, were filled during the two day experiment. One of the integral coincidence spectra is shown in Figure 3. Following the coincidence run, the LEPs detector was used to count the remaining target activity. Because the decay of the two ^{182}Re isomers to states in ^{182}W is well known (Sc 75, Je 74) the resulting apectrum allowed us to estimate that about 90% of the ^{182}Re activity was from the 64 hr isomer.

Timing experiments were performed with the cyclotron beam sweeper and the LEPs detector. The beam sweeper deflects a variable fraction of the cyclotron beam bursts away from the target. Data were taken, controlled by the program TOOTSIE (Ba 71), on the cyclotron Sigma-7 computer during the time the beam is off the target by separating this interval into nine approximately equal time bands. Two time ranges were investigated. In the first the beam was deflected from the target for 8 beam bursts or approximately 400 nsecs. In the second timing experiment alternate beam bursts were deflected with the total time between bursts about 54 nsecs.

A γ-ray angular distribution was performed using a goniometer and the LEPs detector. Data were collected at six angles (taken in random order) relative to the beam direction: 90°, 105°, 115°, 130°, 140°, and 145°. Unfortunately, by the time data were taken at the last angle, 105°, γ-ray peaks from the decay of ^{182}Re to ^{182}W overwhelmed the peaks of interest. This resulted in substantially

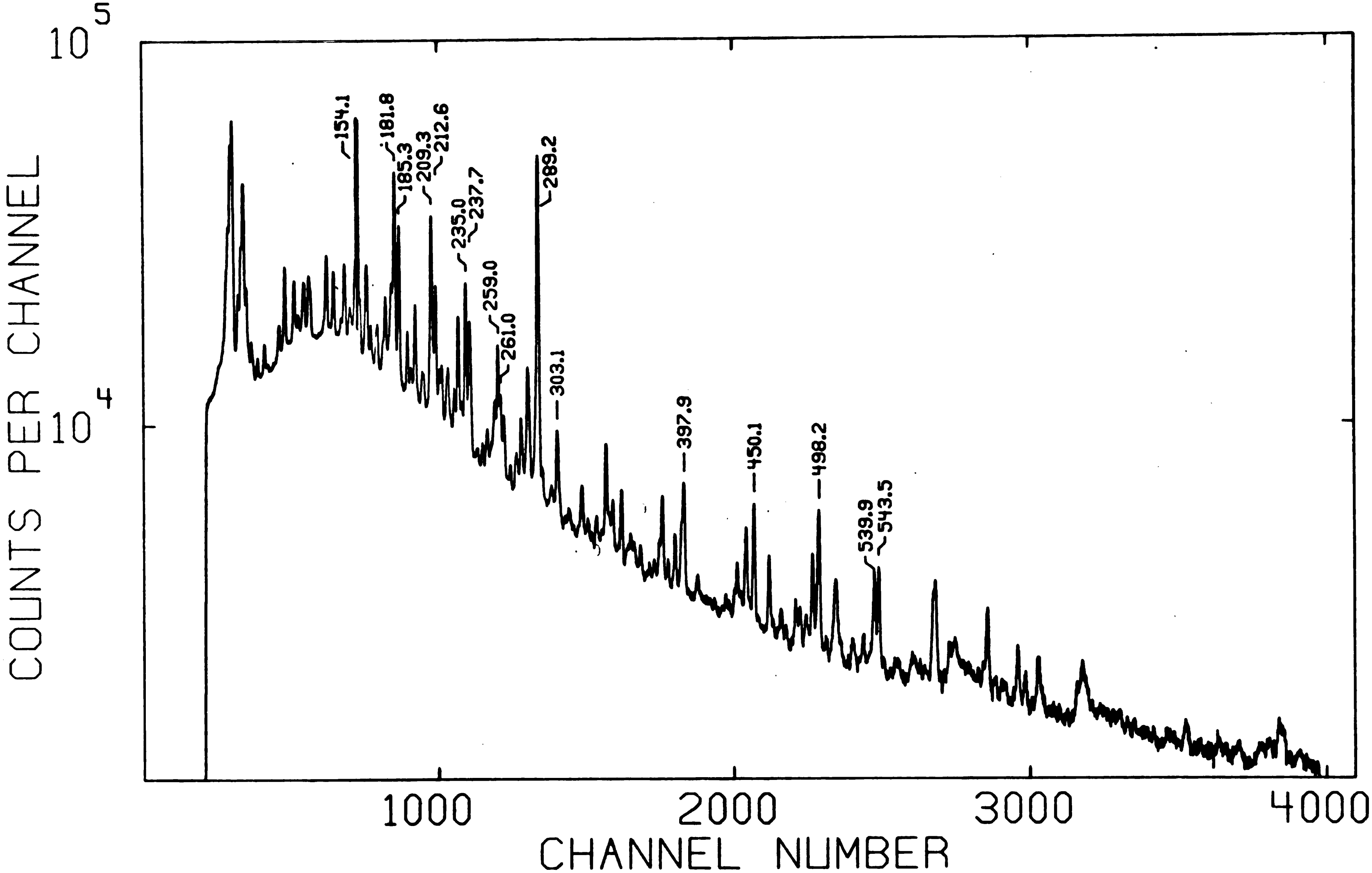

Figure 3. XADC integral coincidence spectrum.

poorer statistics for peak areas of ^{182}Re γ-rays as compared with those obtained for the other angles. γ-rays angular distributions are customarily analyzed in terms of the Legendre polynomials. Figures 4, 5, 6, and 7 show the results for some γ-rays of a least squares fit of the normalized data to

$$W(\Theta) = A_o + A_2P_2(\cos\Theta) + A_4P_4(\cos\Theta)$$

A_2/A_0 and A_4/A_4 coefficients derived from the fit are listed in Table 2. Target and product X-rays were used for the normalization. It was found that better fits were obtained with the 105^o data omitted. This information was therefore ignored in the calculation of the results reported here.

Preliminary singles data shown in Figure 8 from the ^{182}W(p,nγ)^{182}Re reaction indicated that two rotational bands, new to this work and identified in the (α,3nγ) coincidence data, were of low K. In the hope of obtaining more information about these bands another coincidence experiment was undertaken. A 29 MeV proton beam was used to perform the (p,3nγ) reaction on a ^{184}W foil mounted in Formvar. No new information regarding the previously identified bands was obtained so the data were not further analyzed.

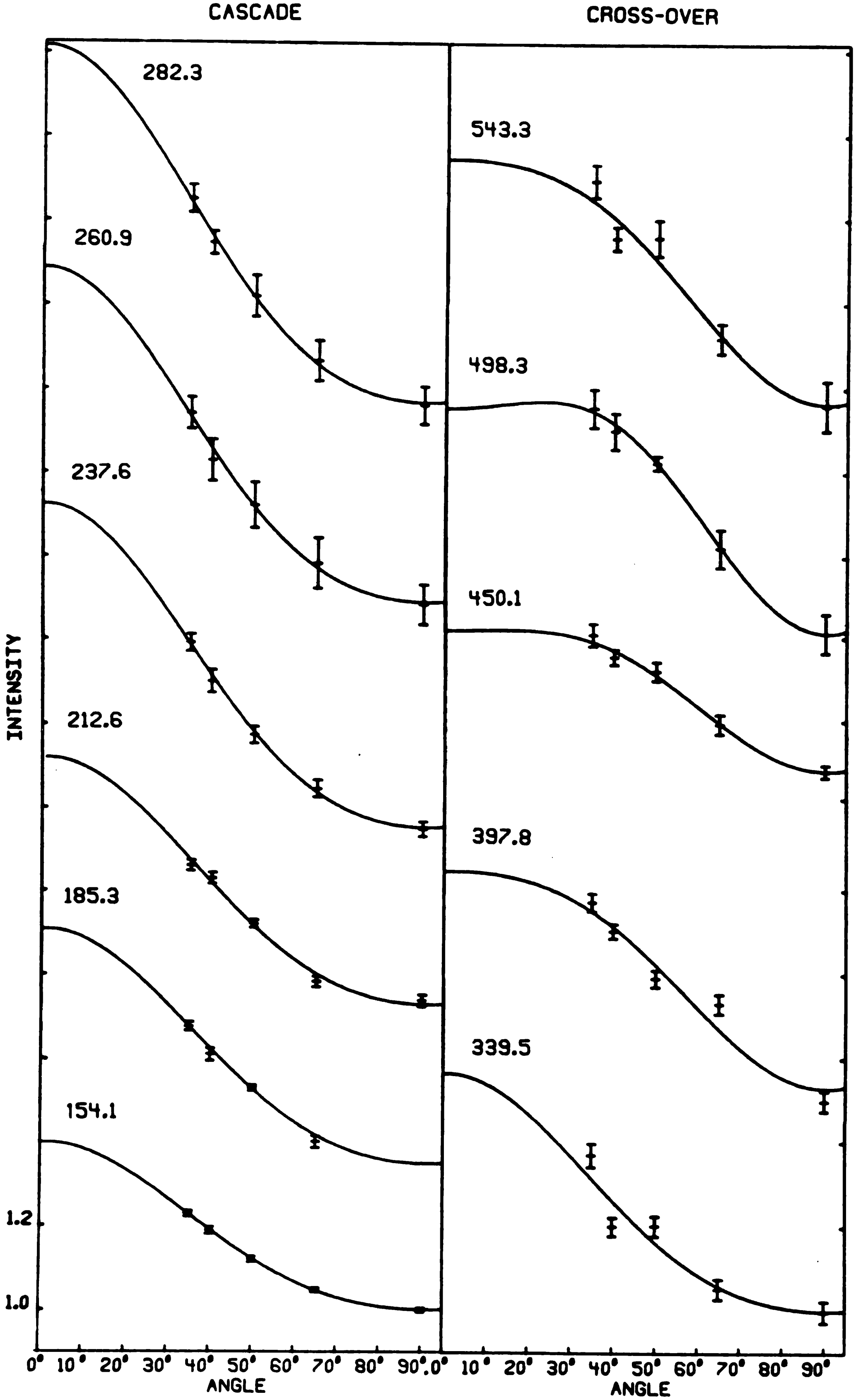

Figure 4. γ-ray angular distribution, 7^+ band.

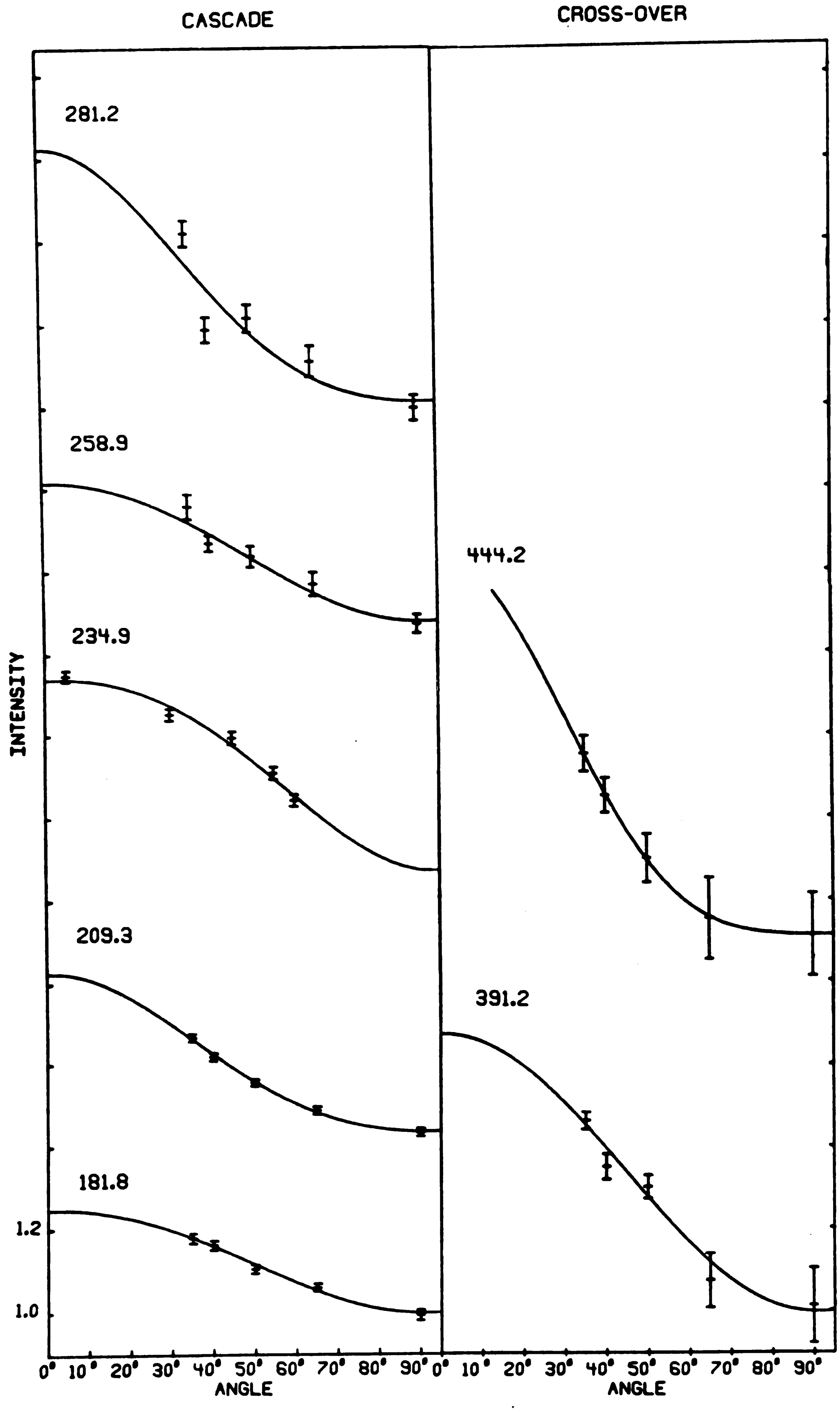

Figure 5. γ-ray angular distribution, 9^- band.

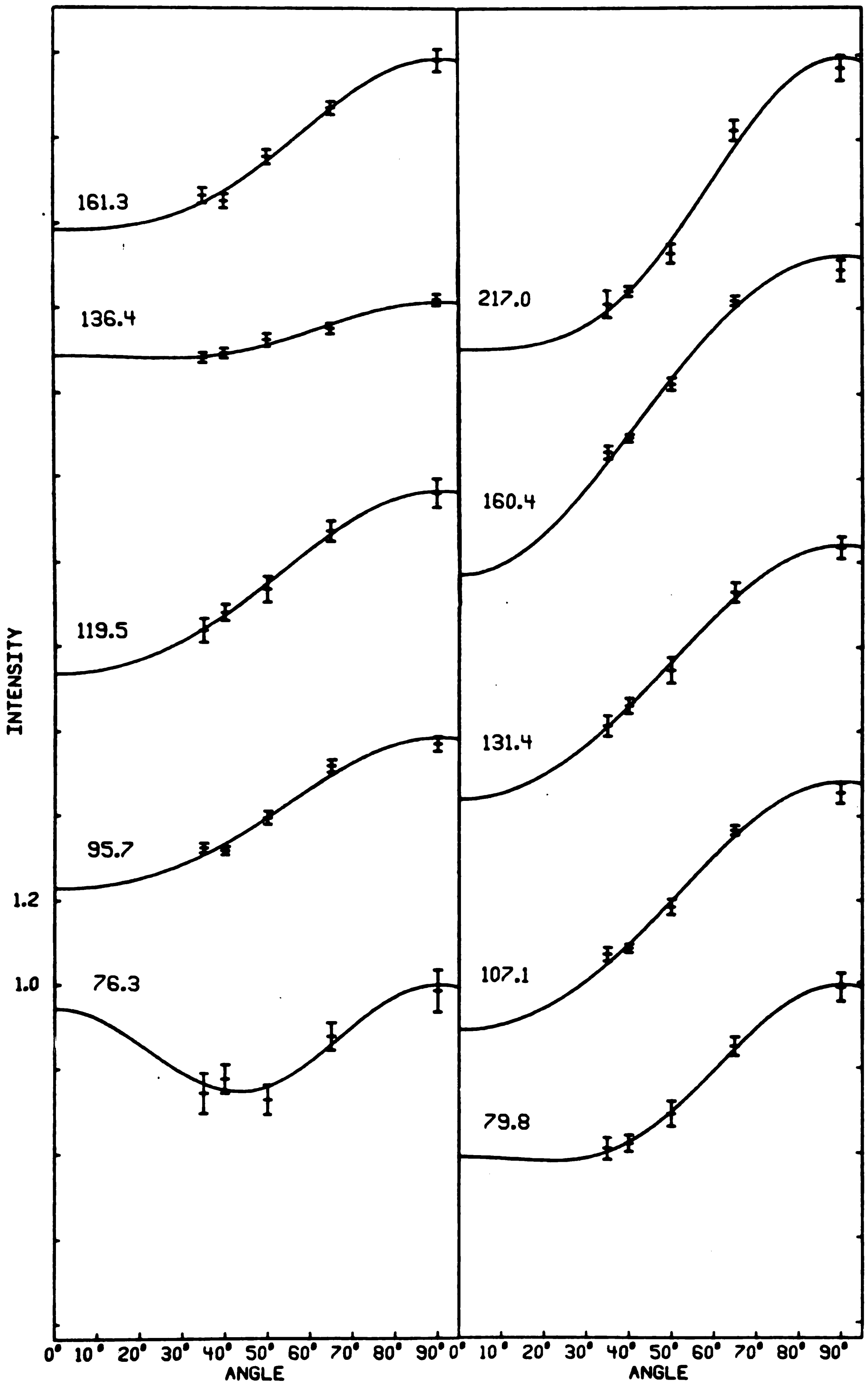

Figure 6. γ-ray angular distribution, 2^+ and 4^- bands.

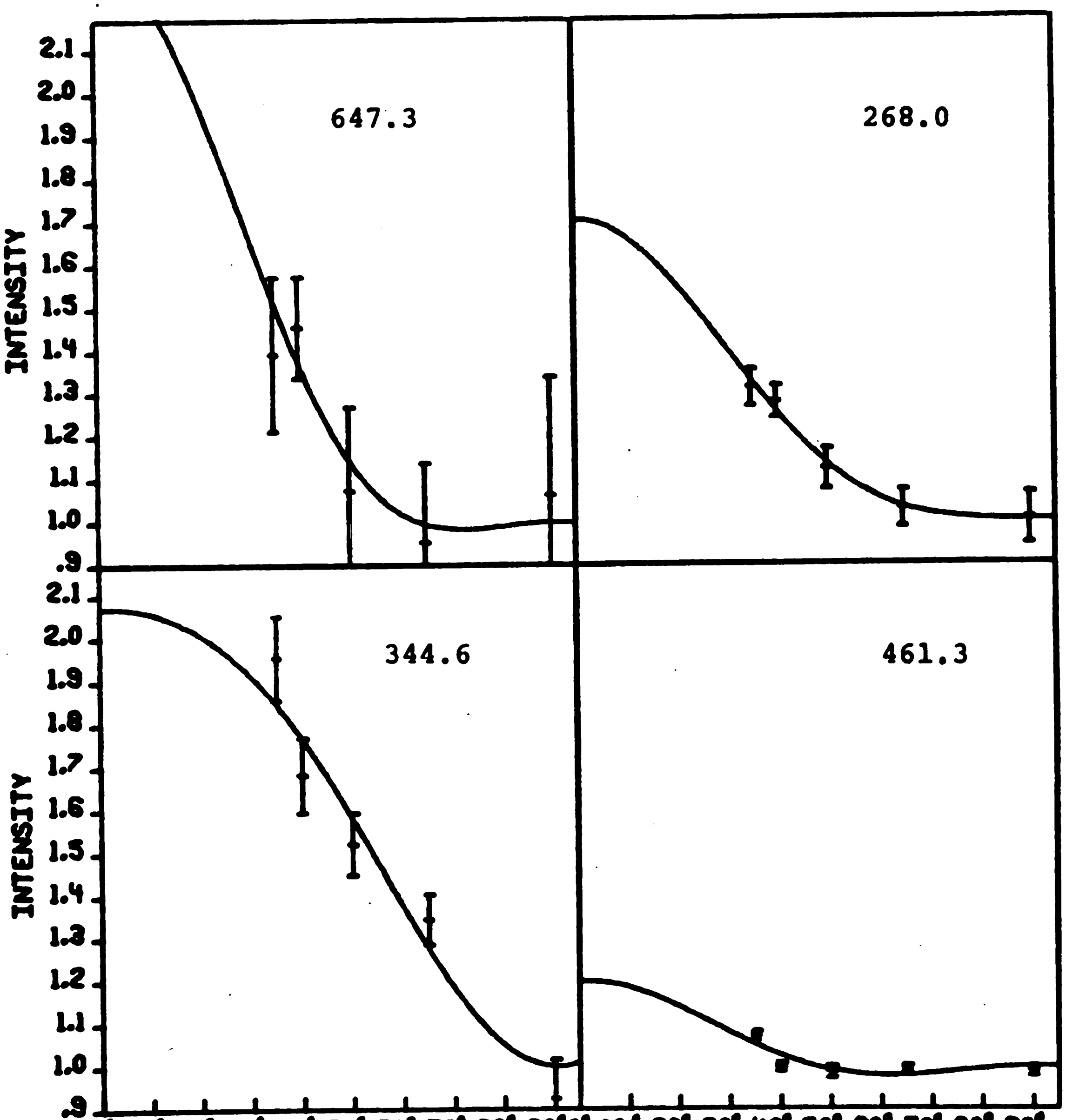

Figure 7. Angular distributions of the 647.3 keV, 268.0 keV, 344.6 keV, and 461.3 keV γ-rays.

TABLE 2

ANGULAR DISTRIBUTION RESULTS

Transition (keV)	Assignment	K	A_2/A_0	A_4/A_0
154.1	$8^+ \rightarrow 7^+$	7	0.227 ± 0.011	0.037 ± 0.013
185.3	$9^+ \rightarrow 8^+$		0.304 ± 0.016	0.044 ± 0.017
212.6	$10^+ \rightarrow 9^+$		0.314 ± 0.027	0.045 ± 0.035
237.6	$11^+ \rightarrow 10^+$		0.396 ± 0.018	0.072 ± 0.023
260.9	$12^+ \rightarrow 11^+$		0.427 ± 0.026	0.081 ± 0.038
282.3	$13^+ \rightarrow 12^+$		0.405 ± 0.030	0.081 ± 0.044
339.5	$9^+ \rightarrow 7^+$		0.304 ± 0.102	0.058 ± 0.137
397.8	$10^+ \rightarrow 8^+$		0.310 ± 0.076	-0.063 ± 0.105
450.1	$11^+ \rightarrow 9^+$		0.224 ± 0.029	-0.072 ± 0.035
498.3	$12^+ \rightarrow 10^+$		0.335 ± 0.017	-0.135 ± 0.018
543.3	$13^+ \rightarrow 11^+$		0.341 ± 0.091	-0.074 ± 0.150
181.8	$10^- \rightarrow 9^-$	9	0.159 ± 0.018	-0.012 ± 0.025
209.3	$11^- \rightarrow 10^-$		0.219 ± 0.012	0.032 ± 0.015
234.9	$12^- \rightarrow 11^-$		0.261 ± 0.036	0.029 ± 0.049
258.9	$13^- \rightarrow 12^-$		0.209 ± 0.058	-0.013 ± 0.075
281.2	$14^- \rightarrow 13^-$		0.325 ± 0.151	0.067 ± 0.203
391.2	$11^- \rightarrow 9^-$		0.368 ± 0.065	0.002 ± 0.106
444.2	$12^- \rightarrow 10^-$		0.451 ± 0.008	0.158 ± 0.012
289.2	$9^- \rightarrow 8^+$	-	-0.147 ± 0.006	0.028 ± 0.009
344.6	$17^+ \rightarrow 15^-$		0.608 ± 0.119	-0.112 ± 0.159
647.3	$17^+ \rightarrow 14^-$		0.591 ± 0.197	0.310 ± 0.317

TABLE 2--Continued

Transition (keV)	Assignment	K	A_2/A_0	A_4/A_0
107.1	$6^- \rightarrow 5^-$	4	-0.382 ± 0.051	0.054 ± 0.091
131.4	$7^- \rightarrow 6^-$		-0.384 ± 0.024	0.026 ± 0.036
160.4	$8^- \rightarrow 7^-$		-0.469 ± 0.036	-0.021 ± 0.063
217.0	$10^- \rightarrow 9^-$		-0.527 ± 0.059	0.142 ± 0.086
95.7	$5^+ \rightarrow 4^+$		-0.223 ± 0.031	0.032 ± 0.048
119.5	$6^+ \rightarrow 5^+$		-0.266 ± 0.018	0.032 ± 0.028
161.3	$8^+ \rightarrow 7^+$		-0.271 ± 0.027	0.065 ± 0.043

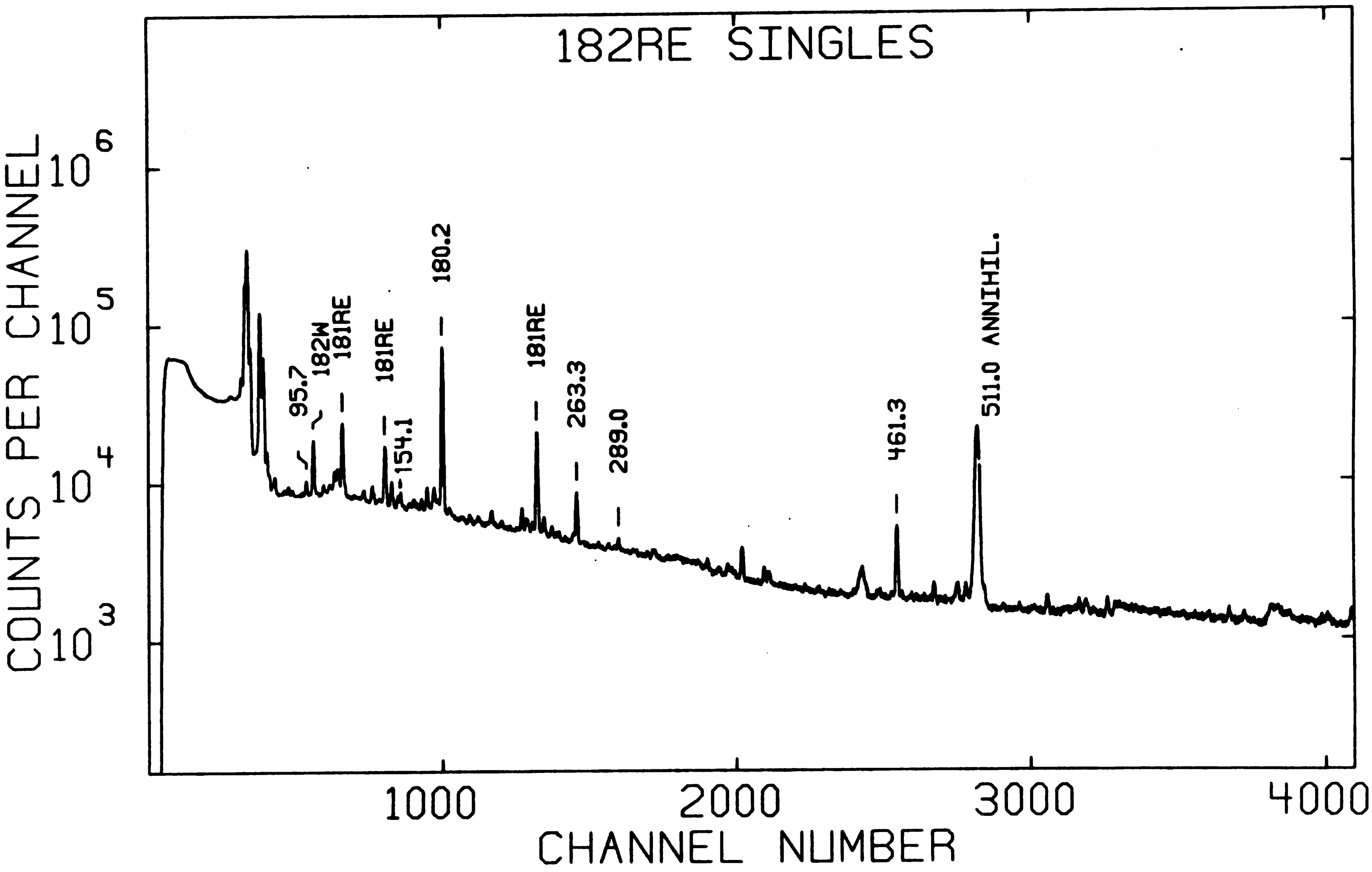

Figure 8. γ-ray singles from the $^{182}W(p,n\gamma)^{182}Re$ reaction.

LEVEL ASSIGNMENTS: 7^+ AND 9^- BANDS

The single particle levels of a deformed nucleus can be calculated in the Nilsson model from the quadruple and hexadecapole deformation parameters ε_2 and ε_4, the spin-orbit coupling parameter κ, and the parameter μ which functions to depress states of high angular momentum (Ni 70). Because these parameters vary slowly over the region their values can be estimated by taking the average of those experimentally deduced for the neighboring even-even tungsten and osmium nuclei. In this manner we obtain ε_2=0.24 and ε_4=0.05. The other parameters can be determined from equations given by Nilsson and Tsang (Ni 69). Single particle levels calculated from these parameters are shown in Figures 9 and 10 compared to experimentally determined levels for neighboring odd A nuclei (Ea 73, Ar 75). The ground state of ^{182}Re is therefore expected to result from the coupling of the $5/2^+[402\uparrow]$ proton and the $9/2^+[624\uparrow]$ neutron. Recent atomic beam experiments (Ru 75) have established that the 12.7 hr isomer has spin 2, probably from the singlet coupling of the above particles. No measurements for the longer lived 64 hr isomer were reported. However, log ft values deduced by Sapyta et al. (Sa 70) indicate that the 64 hr isomer has spin and parity 7^+, 6^+, or 6^-. This result is consistent with the triplet coupling $7^+\{5/2^+[402\uparrow] \otimes 9/2^+[624\uparrow]\}$. The coupling rules of Gallagher and Moszkowski (Ga 58) predict that for odd-odd nuclei the triplet coupling will

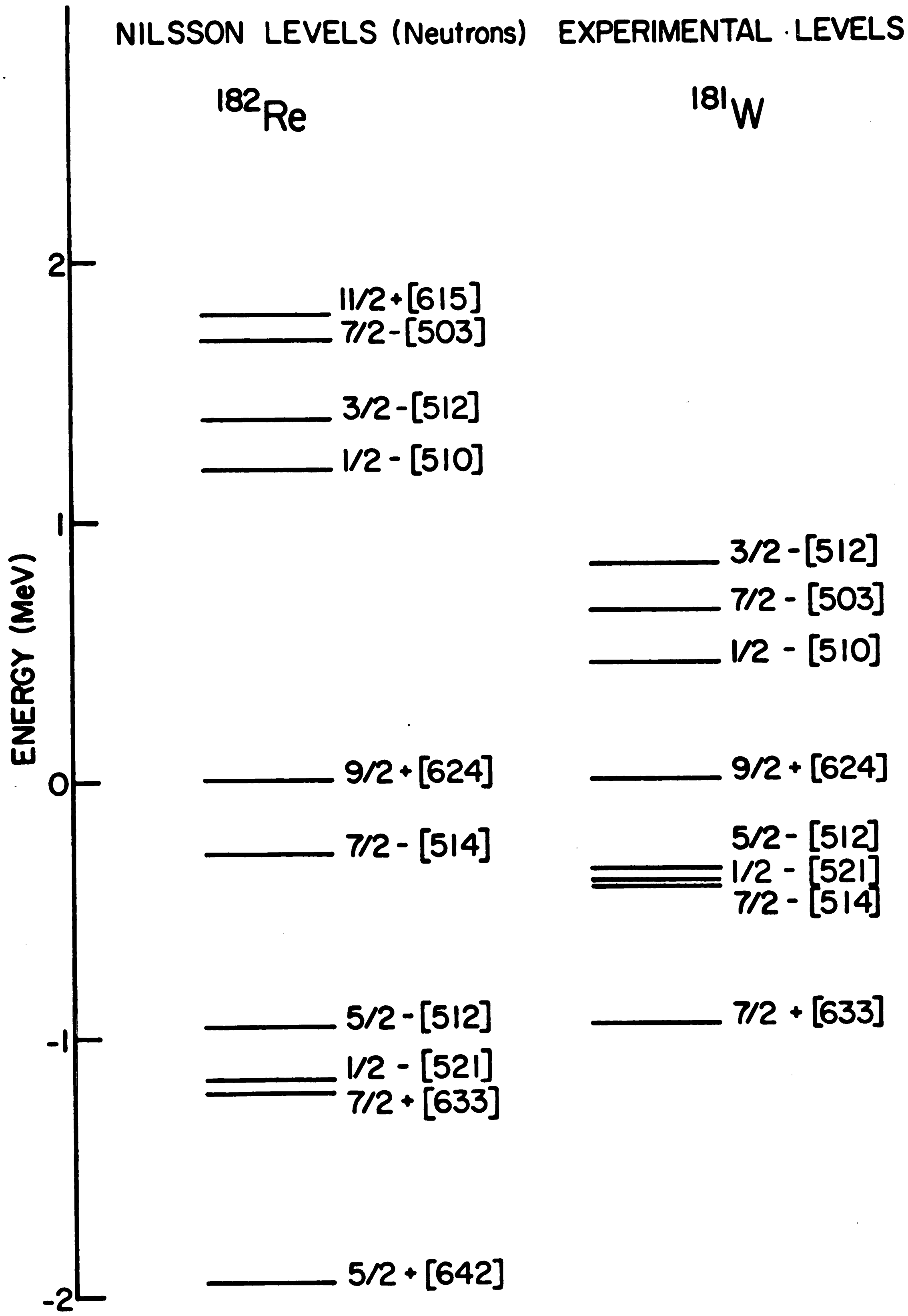

Figure 9. Theoretical and experimental levels--neutron.

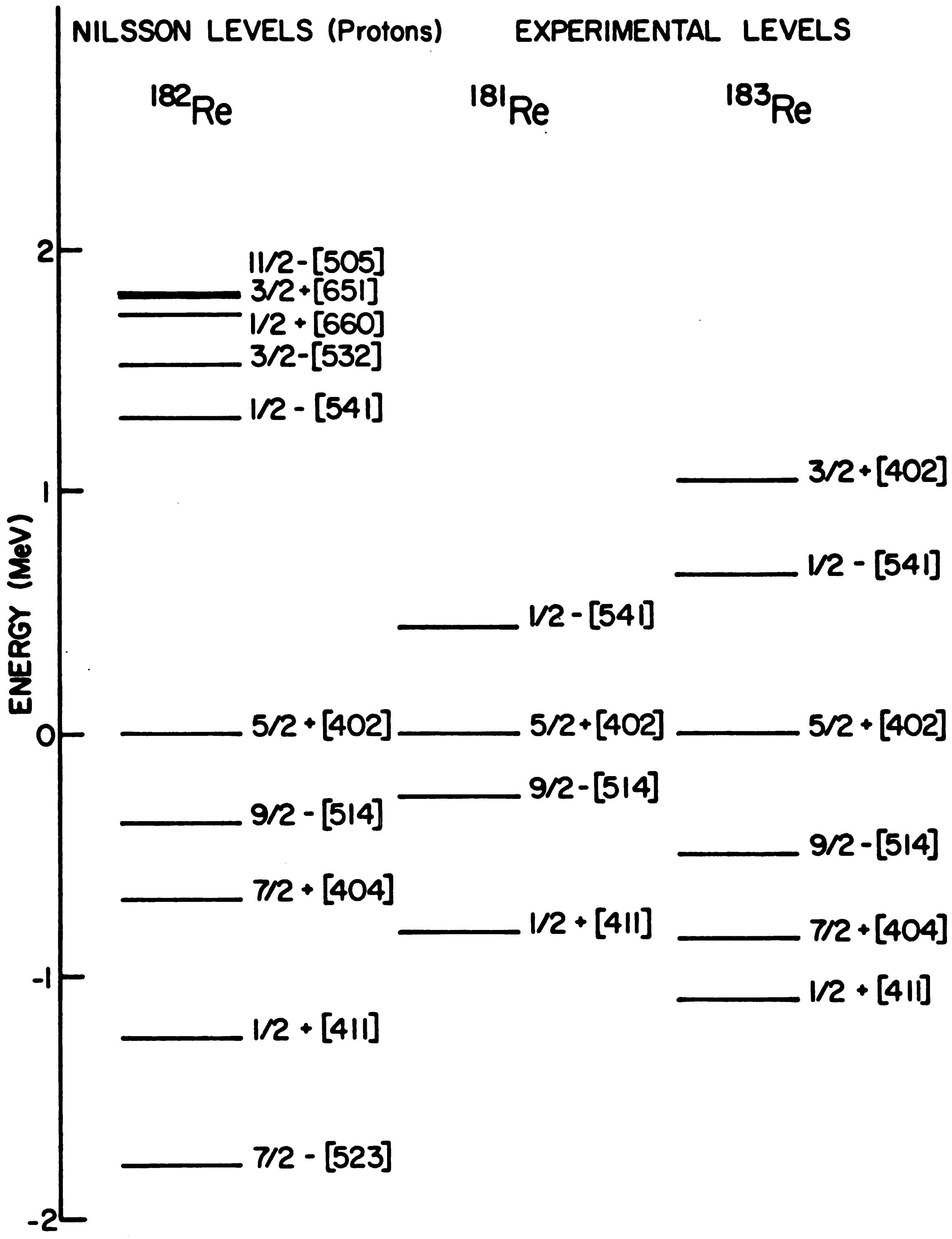

Figure 10. Theoretical and experimental levels--protons.

produce the lower energy state. Therefore, the expected ground state spin and parity are 7^+. Unfortunately, because of the large spin difference, no communication between the two isomers is anticipated, so the above prediction cannot be verified. Nevertheless, for the purposes of this work, we will consider the 64 hr isomer to be the ground state.

According to this assignment the level scheme constructed from the coincidence data is shown in Figure 11. Members of the two rotational bands reported by Hjorth et al., here assigned to be the 7^+ and 9^- bands respectively, were prominent in the integral coincidence spectra. However, as reported independently by Medsker et al., gates set on these transitions shown in Figures 12-13 indicate that the arrangement of the two bands is opposite to that proposed by Hjorth et al. with the 154.1 keV transition of the lower band being fed by members of the upper band via the 289.0 keV transition.

Gates set on the 154.1 keV peak reveal only the γ-rays known to be feeding that level. There are no other unplaced γ-rays in the singles spectrum of sufficient intensity to deexcite the level fed by the 154.1 keV transition. Therefore this transition must directly feed either the 2^+ or the 7^+ isomer. Because the $(\alpha,3n\gamma)$ reaction populates states which decay mostly to the 7^+ isomer, the latter situation is more likely. Level systematics and γ-ray angular distributions support the assignment of the 154.1 keV level to the 8^+ member of the

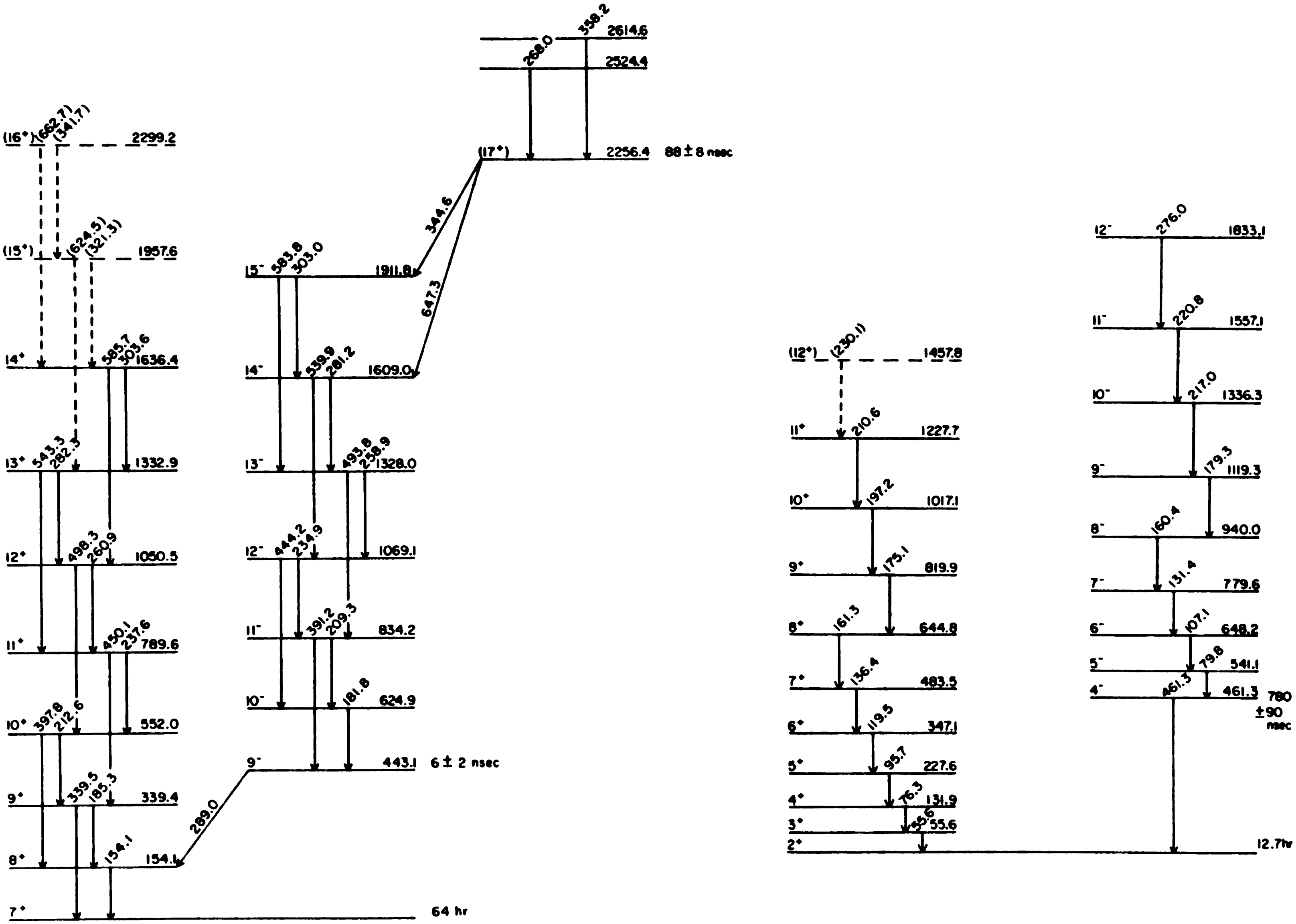

Figure 11. Level scheme.

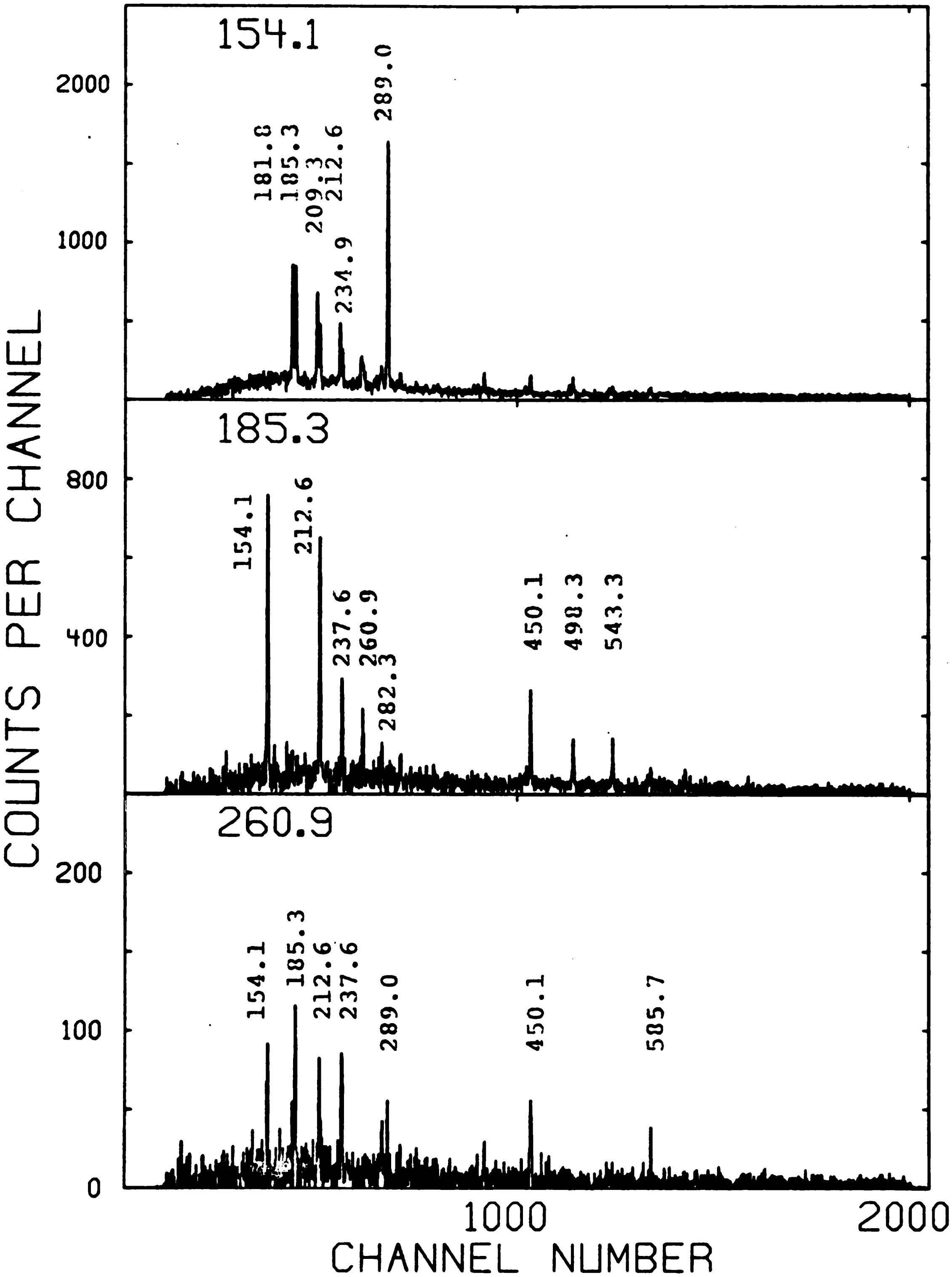

Figure 12. Coincidence gates associated with the 7^+ band.

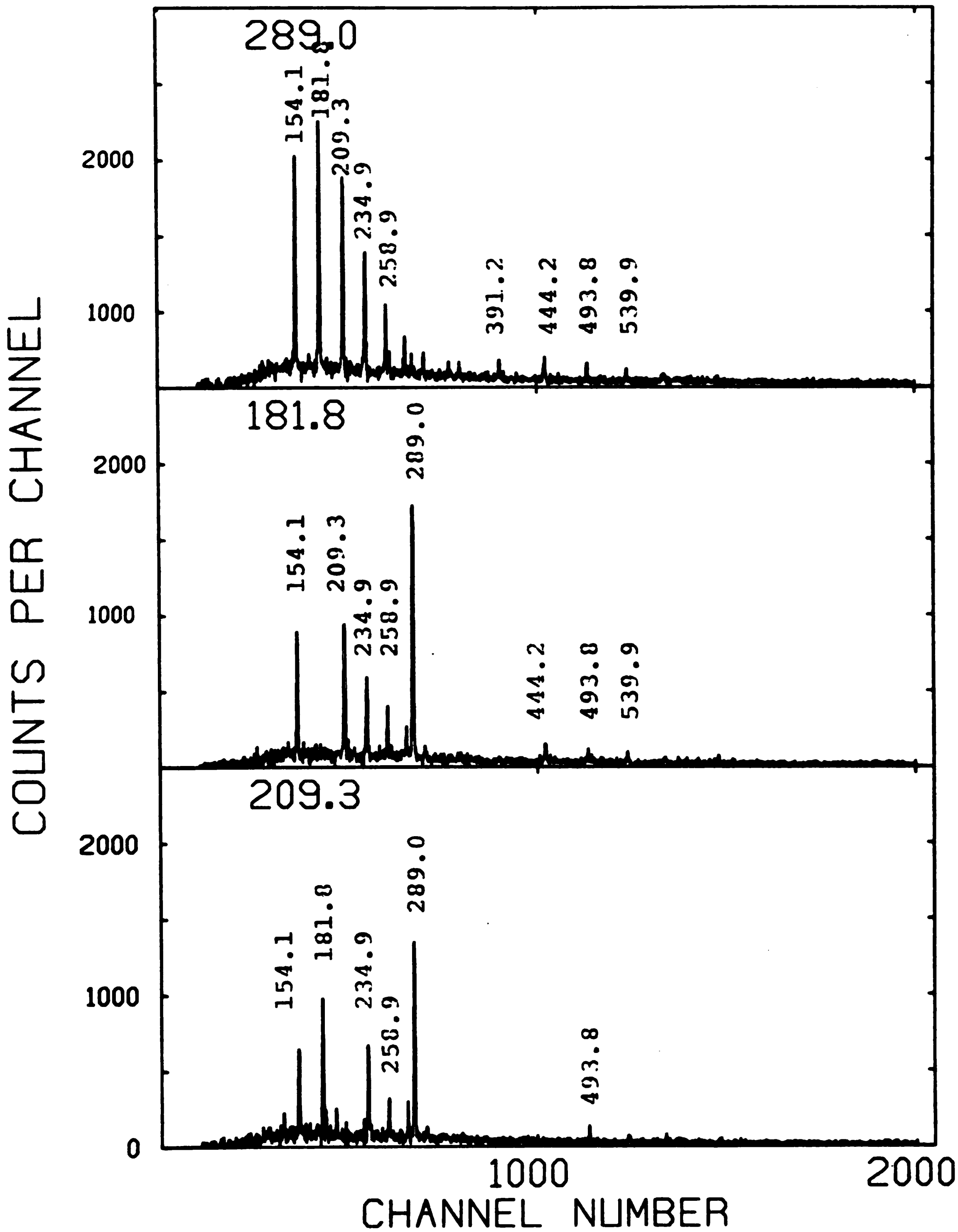

Figure 13. Coincidence gates associated with the 9^- band.

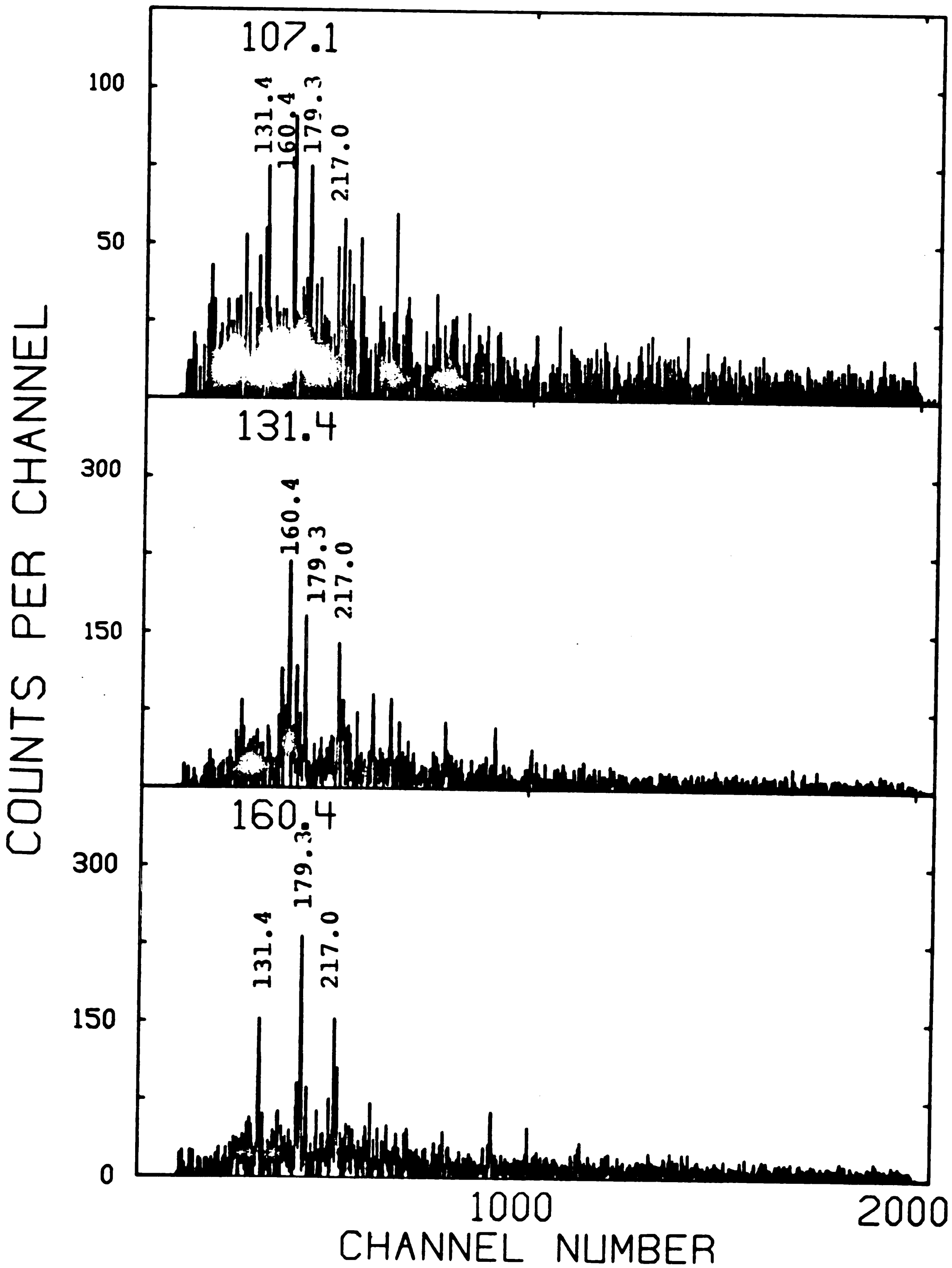

Figure 14. Coincidence gates associated with the 4^- band.

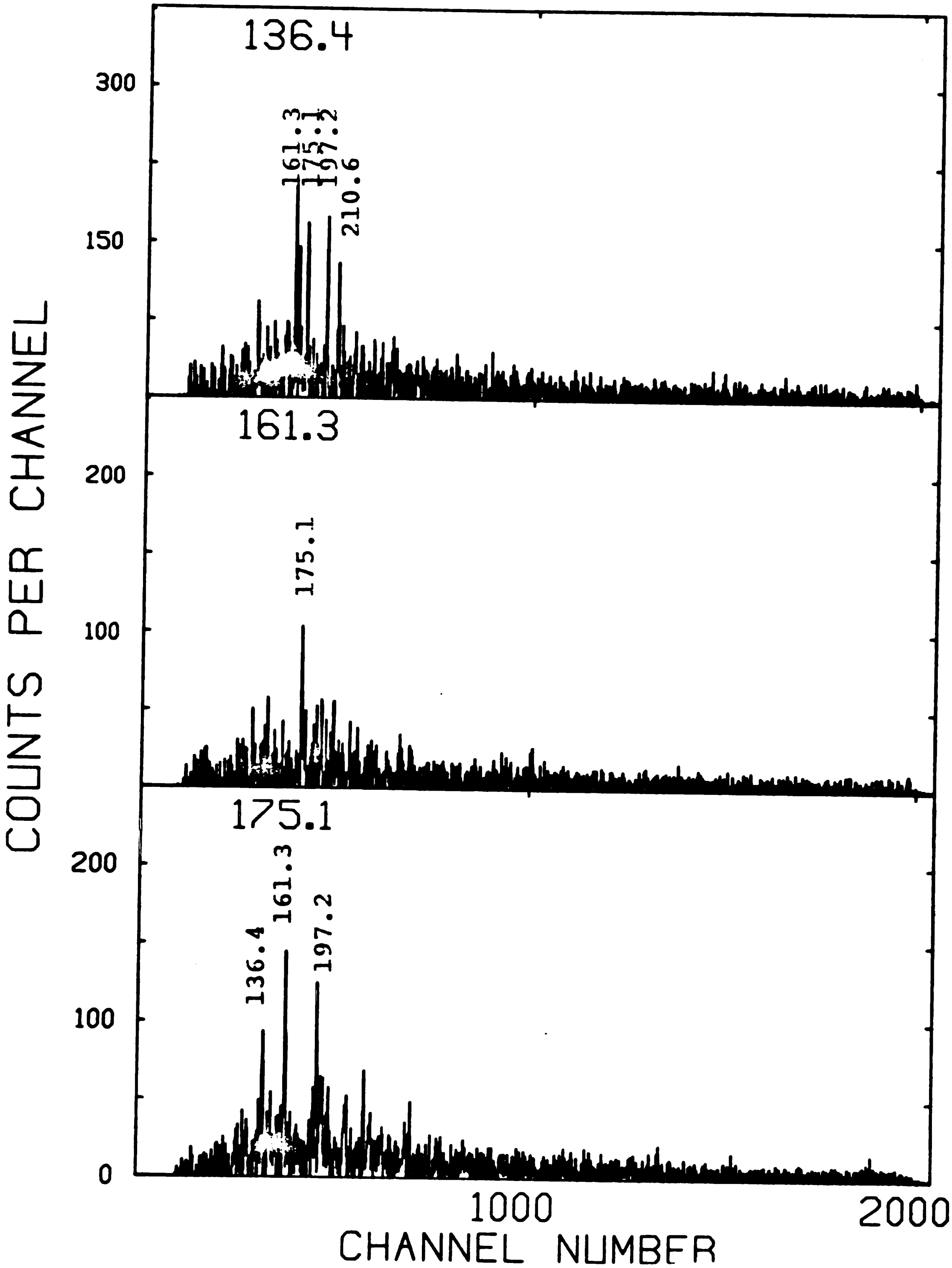

Figure 15. Coincidence gates associated with the 2^+ band.

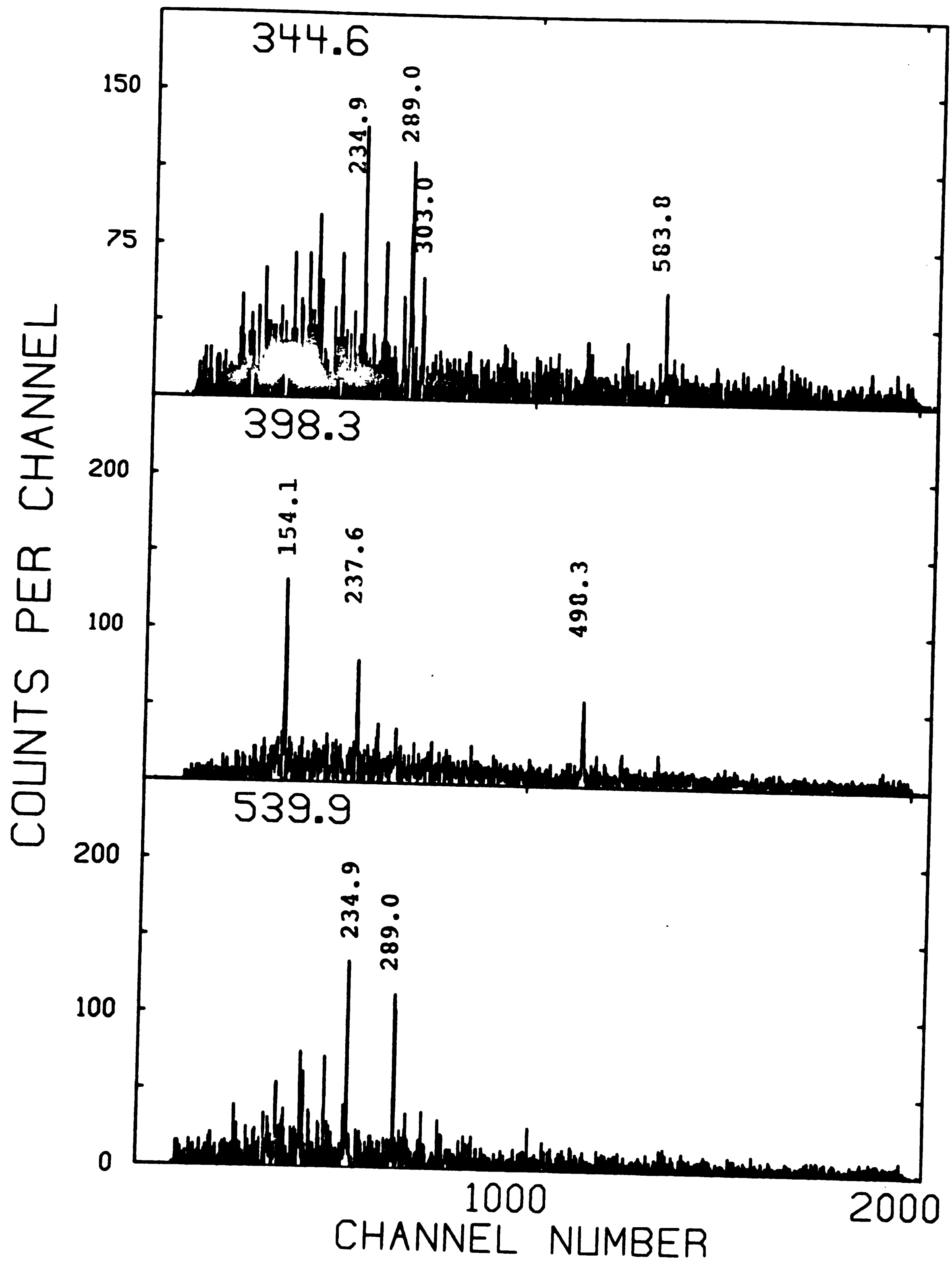

Figure 16. 344.6 keV, 398.3 keV, and 539.9 keV coincidence gates.

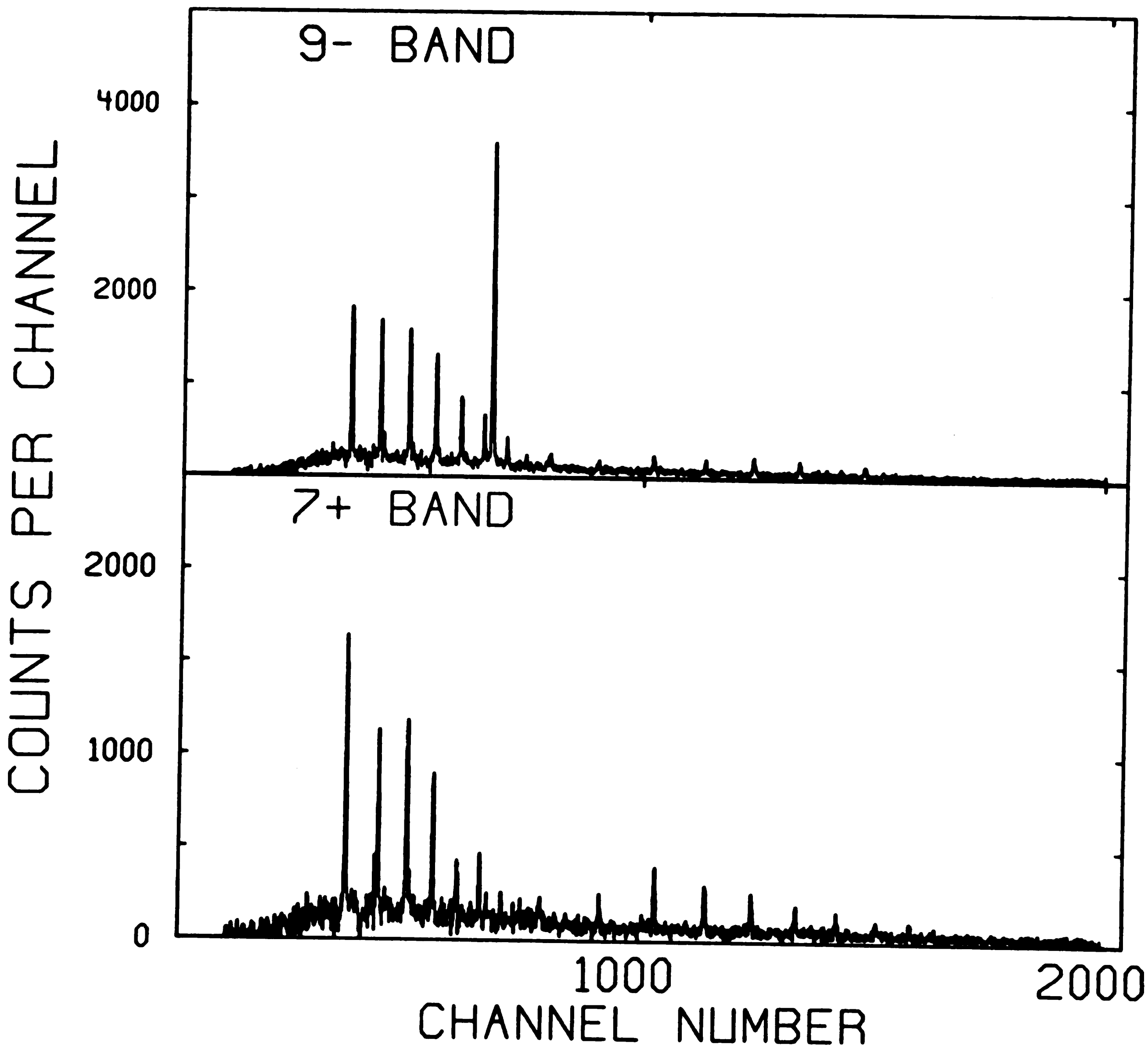

Figure 17. Spectra created by summing gates set on members of the 7^+ and 9^- bands.

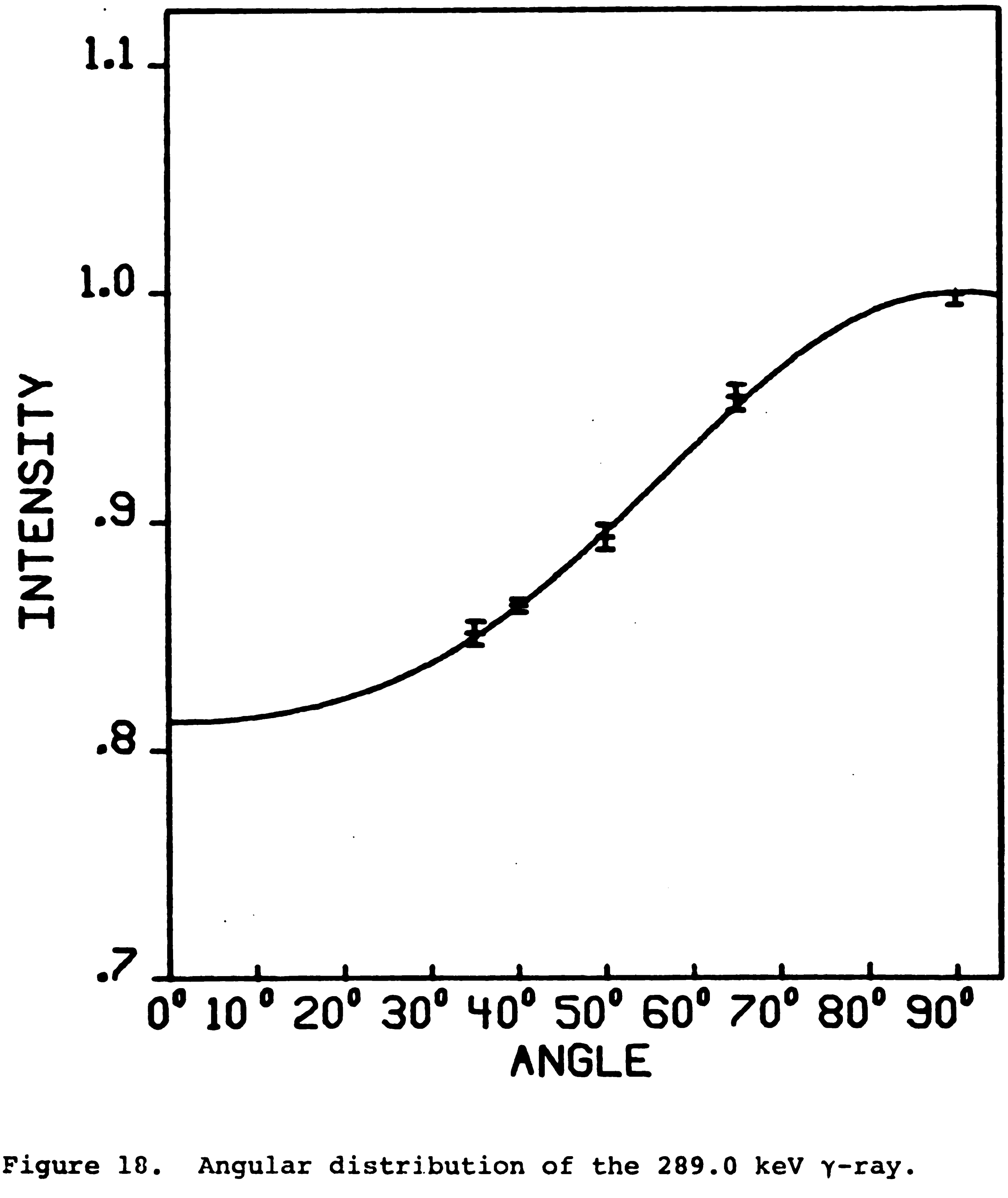

Figure 18. Angular distribution of the 289.0 keV γ-ray.

K = 7 ground state rotational band. Similar reasoning applies to the assignments of other intraband transitions. The 281.2 keV and 282.3 keV peaks are not resolved in the integral coincidence spectrum, but by selectively gating over portions of the composite peak it was possible to assign them unequivocally to the 7^+ and 9^- bands respectively. A similar procedure was carried out for the doublets at 303 keV and 585 keV.

The assignment of 9^- to the 443.3 keV level is based on several experimental and theoretical considerations. The angular distribution of the 289.0 keV transition is shown in Figure 18. This can be compared to various theoretical angular distributions for transitions feeding an 8^+ level (Figure 19) (Mc). Theoretical curves are given only for transitions from states with spin greater than or equal to 8. The 443.3 keV level is assumed to have spin greater than or equal to 8 for two reasons. First, the nucleus deexcites almost exclusively along the yrast line toward states of lower spin. Secondly, for initial states with spin less than 8, the transition directly to ground should dominate. A comparison of the experimental and theoretical angular distributions demonstrates that the 289.0 keV transition is either a stretched dipole or an $8 \rightarrow 8$ quadrupole transition. Inside rotational bands E2 transitions are enhanced; however, such is not the case here and a pure quadrupole $8 \rightarrow 8$ transition is unlikely. Instead, a transition from a spin 8 level would probably feed the spin 7 level. It should be

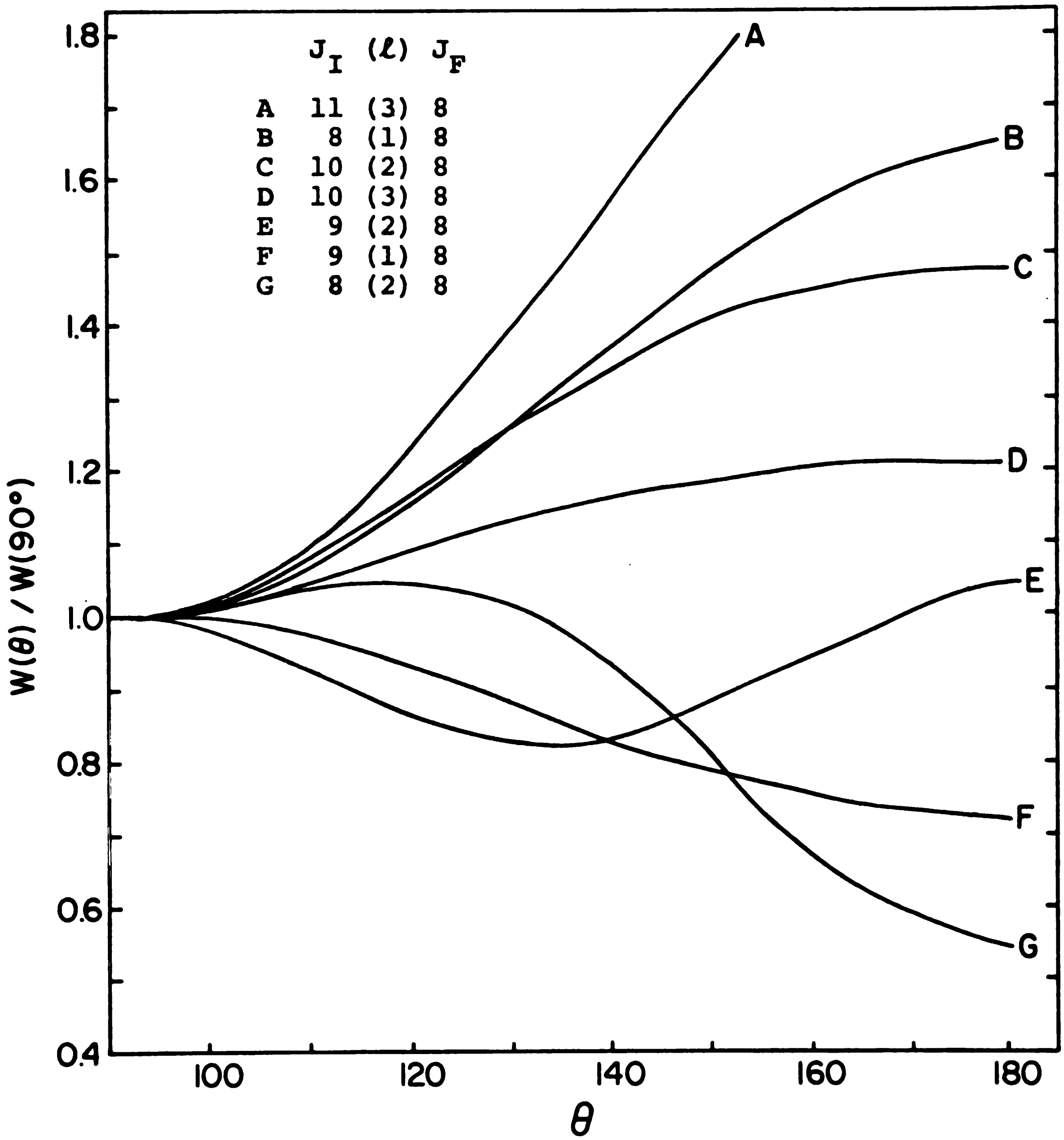

Figure 19. Theoretical angular distributions for γ-rays feeding an 8^+ level.

noted, however, that a pure dipole transition would be one-degree K-forbidden. This is expected to hinder the transition by approximately one order of magnitude. Also, E1 transitions have been found to be strongly hindered over the Weisskopf estimates in this region of the periodic table. A typical hindrance factor is 10^6 (En 66). Nevertheless, a crude calculation from which one expects only order of magnitude results, assuming a hindrance factor of 10^6 (this value also agrees with that obtained from corresponding E1 transitions in ^{181}Re and ^{183}Re), predicts approximately equal quadrupole and dipole components for the 289.0 keV interband transition.

Another argument against the K = 8 assignment for the 443.1 keV level is seen by referring to the theoretical levels of Figures 7 and 8. The only two-quasiparticle configurations which satisfy the conditions imposed by the angular distribution of the 289.0 keV γ-ray are the triplet coupling of the $9/2^-[514\uparrow]$ proton to the $9/2^+[624\uparrow]$ neutron to form a 9^- state and the singlet coupling of the $7/2^+[404\downarrow]$ proton to the $9/2^+[624\uparrow]$ neutron to give an 8^+ state. As indicated by the figures, the 9^- state is energetically favored and therefore should be much more strongly populated.

A final argument, and probably the strongest, in favor of the proposed assignment is also entirely model dependent. As explained in a later section on g-factors, the intrinsic gyromagnetic ratio g_K, obtained for the rotational band built on the 443.1 keV level, is inconsistent with the $8^+\{7/2^+[404\downarrow] \otimes 9/2^+[624\uparrow]\}$ assignment but does agree with the $9^-\{9/2^-[514\uparrow] \otimes 9/2^+[624\uparrow]\}$ assignment.

The timing experiment with the 54 nsec time scale established that the 154.1 keV and 289.0 keV γ-rays are delayed with a half-life of 6 ± 2 nsecs. From the coincidence data and the measured intensities of the 181.8 keV, 391.2 keV, and 289.0 keV γ-rays, it is clear that the 443.1 keV level is significantly fed only by members of the 9^- band. Therefore we conclude that this level is isomeric.

Data from the "slow" timing experiment established that all members of the 9^- band are delayed. The measured half-life, determined from the half-life curves of two of the most easily fit peaks, is 88 ± 8 nsecs (see Figure 20). Coincidence data reveal that the 15^- and 14^- levels of the 9^- band are fed by transitions of 344.6 keV and 647.3 keV. A placement of these transitions within the band is contrary to predicted rotational behavior as shown by the plot of $E_I - E_{I-1}/2I^2$ in Figure 21. Consequently, in the level scheme of Figure 9 these transitions are shown deexciting a level of 2256.4 keV which is not placed in the band.

In the coincidence experiment the time between events is recorded as one of the parameters. The integral time (TAC) spectrum, formed by accepting all events within the time interval range determined by the apparatus, is

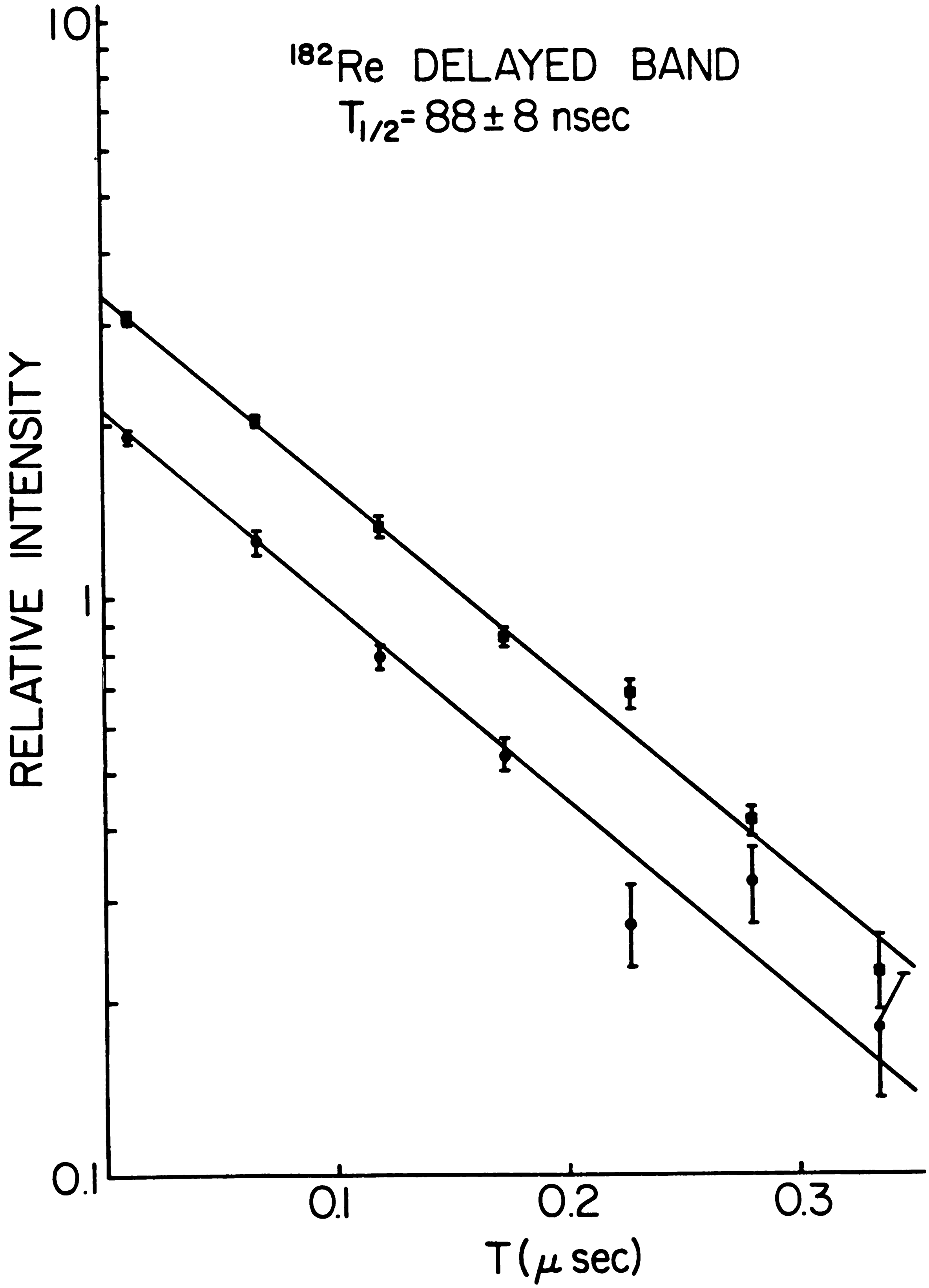

Figure 20. $T_{1/2}$ curves for members of the 9^{-} band.

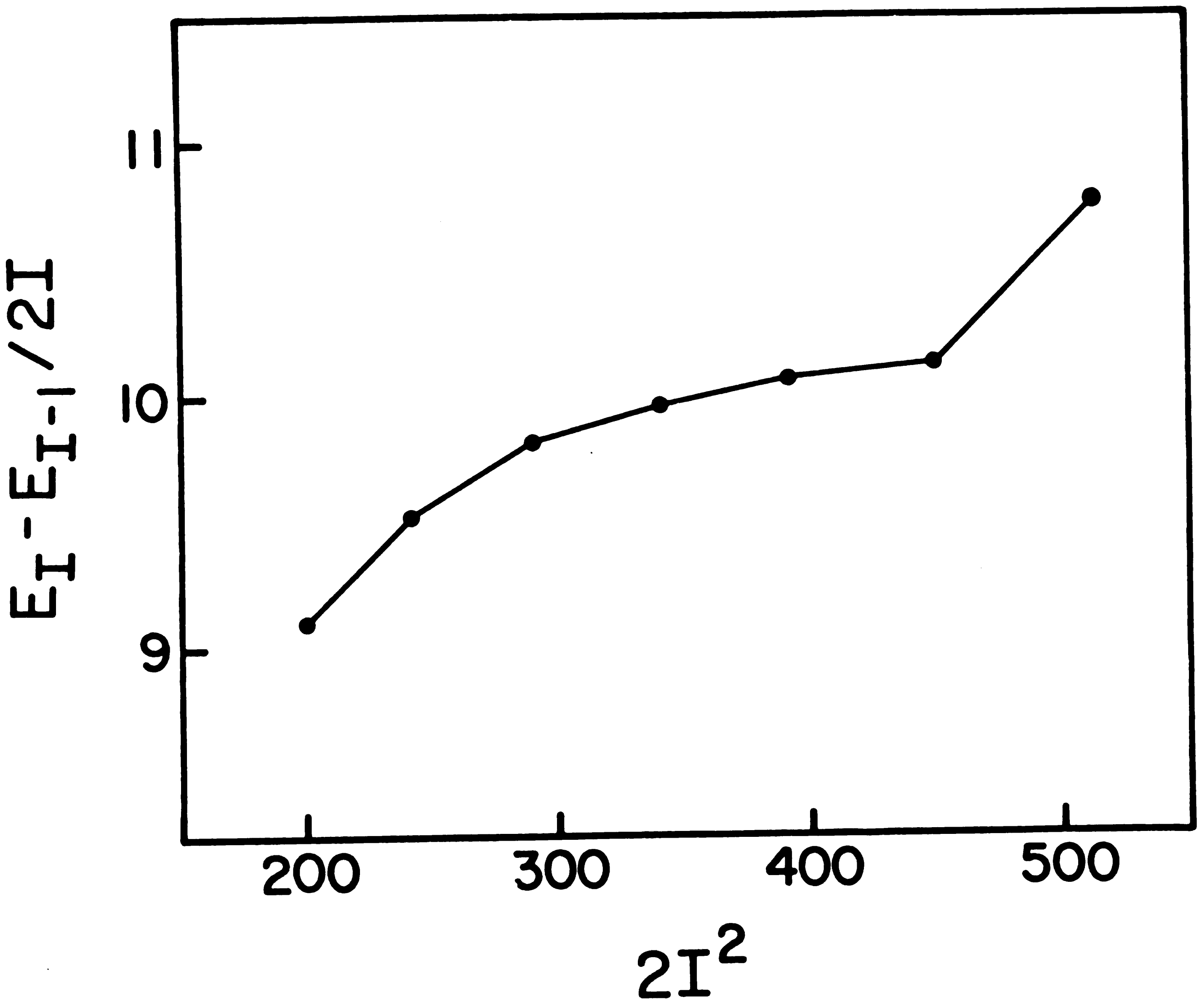

Figure 21. $(E_I - E_{I-1})/2I$ for the 9^- band. The last point results from an attempt to place the 2256.4 keV level in the band.

characterized by a sharp peak, typically 15 nsec FWHM (full width at half maximum), corresponding to prompt events. By setting coincidence gates off the prompt peak transitions feeding an isomeric level can be emphasized. In the delayed coincidence gate thus produced, peaks from delayed transitions will appear more intense than those from prompt transitions. Delayed coincidence gates on easily resolved members of the 9^- band were summed and an appropriate fraction of the integral coincidence spectrum subtracted to partially eliminate prompt and chance contamination. From the resulting spectrum, Figure 22, we conclude that transitions of 268.0 keV and 358.2 keV feed the isomeric level at 2256.4 keV. These two γ-rays are not in coincidence with each other. As a check, delayed coincidence gates were set on these peaks to emphasize transitions deexciting the isomeric level. Only the 344.6 keV and 647.3 keV peaks and members of the 9^- band appear in both gates. Therefore, we conclude that the isomeric level decays exclusively through the 9^- rotational band.

The angular distributions of γ-rays from the 344.6 keV and the 647.3 keV transitions are characterized by positive A_2 coefficients. This establishes that neither are stretched dipole transitions. The angular distribution of the 344.6 keV γ-ray is consistent with the assignment of spin 15 to the 2256.4 keV isomeric level. In that case the 647.3 keV γ-ray would have to be a quadrupole 15→14 transition. The 647.3 keV transition is quite intense relative to

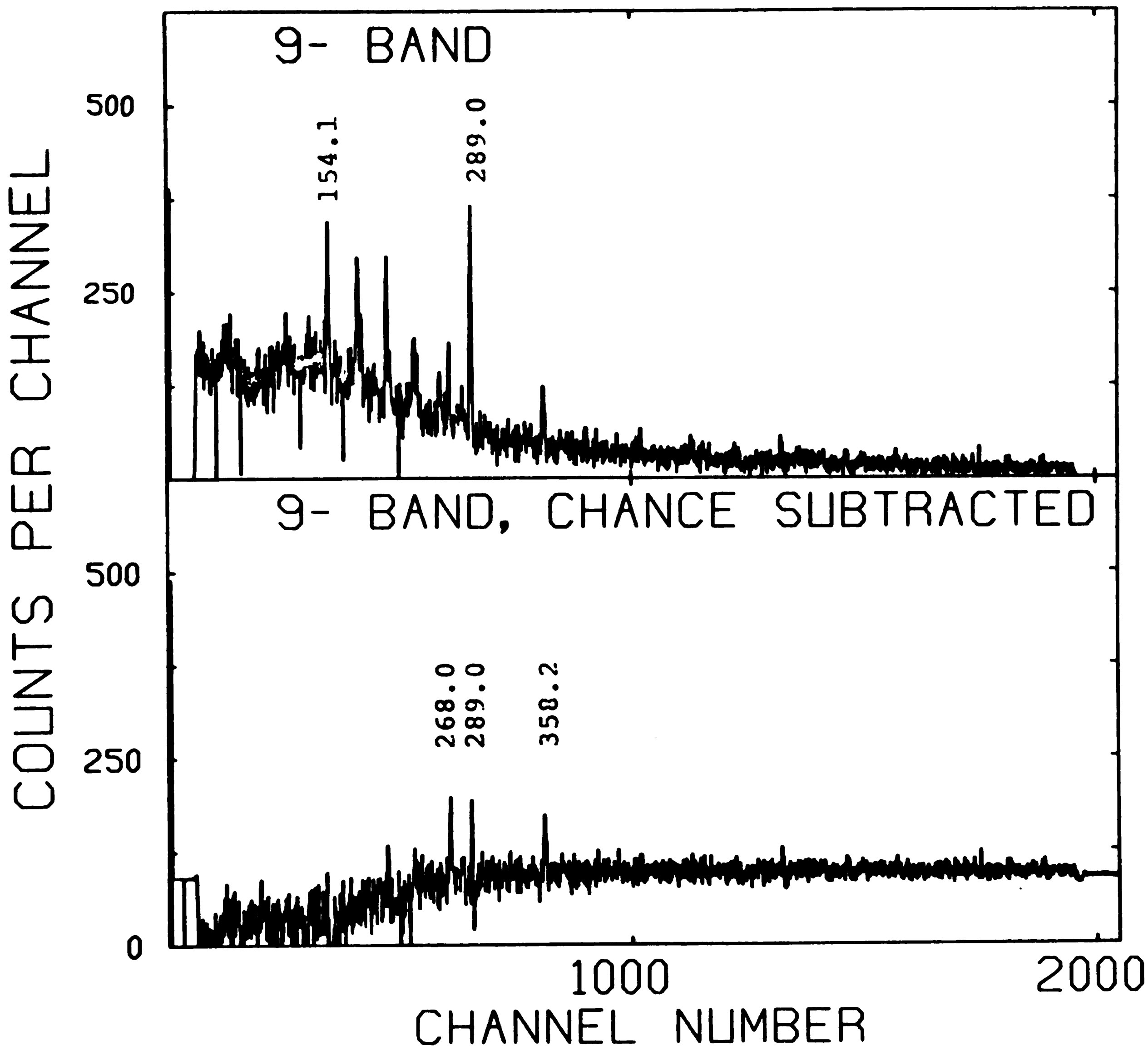

Figure 22. Spectra created by summing delayed coincidence gates set on members of the 9^- band.

the 344.6 keV transition. Therefore the 344.6 keV is probably M1 and the 647.3 keV transition probably E2. Electromagnetic selection rules then require that the 2256.4 keV level have negative parity. For more definite assignments, improved angular distributions of the 344.6 keV and 647.3 keV γ-rays are required. Unfortunately, the isomeric nature of the 2256.4 keV level will severely hinder the attainment of a conclusive result.

No conclusions about the spin of the 2524.6 keV level can be drawn from the angular distribution of the 268.0 keV γ-ray feeding the isomeric level. The angular distribution only rules out stretched dipole transitions. The angular distribution of the 358.2 keV γ-ray was not determined.

LEVEL ASSIGNMENTS: 2^+ AND 4^- BANDS

Two other rotational bands were observed. The more strongly populated of these two bands is built on a level at 461.3 keV above the 2^+, 12.7 hr isomer. Because the energy difference between the 7^+, 64 hr isomer and the 2^+, 12.7 hr isomer is not known, only relative energies can be given. Consequently, the level energies of Figure 11 for the proposed 2^+ and 4^- bands are taken relative to the 2^+ isomer. Also the energy of the 2^+ level is shown in the figure to be slightly higher than that of the 7^+ level as expected from the Gallagher-Moszkowski coupling rules. There is no direct evidence for this assignment.

Timing data established that the 461.3 keV transition is delayed with a half-life of 780 $\pm$ 90 nsecs. No γ-ray peaks are seen in coincidence gates set on the 461.3 keV γ-ray peak or in delayed coincidence gates set to emphasize transitions deexciting isomeric levels fed by the 461.3 keV transition. Therefore we conclude that the 461.3 keV transition feeds directly either the 7^+ or the 2^+ isomer. Delayed coincidence gates verify that a rotational band is built on the 461.3 keV level. Peaks at 107.1 keV, 131.4 keV, and 160.4 keV are seen in the delayed coincidence gate set on the 461.3 keV transition. Higher spin members of the band are found in prompt coincidence gates set on these transitions.

The 79.8 keV transition to the 461.3 keV level is not seen in prompt coincidence gates set on other members of the band. This is due to an instrumental problem occurring because the prompt peak of the TAC spectrum becomes drastically spread out for γ-rays of energy below about 100 keV. Prompt coincidence gates are normally set on the prompt peak of the integral TAC spectrum and the chance coincidence background is subtracted. For low energy γ-rays this procedure effectively subtracts most of the coincidence events. However, for delayed coincidence gates no background subtraction is performed so coincidence events from low energy transitions are seen. The 79.8 keV transition is seen in delayed coincidence gates set on the 107.1 keV and 131.4 keV transitions and figures prominently in the spectrum created by summing the delayed coincidence gates set on other band members as seen in Figure 23. No information about the lifetime of the 79.8 keV transition can be derived from the coincidence data. However the timing experiments establish that the transition is prompt, as is required of transitions within a rotational band. Furthermore, the energy, intensity, and angular distribution of the 79.8 keV γ-ray are consistent with its placement in the band.

The spacing of the rotational levels of the band built on the 461.3 keV isomeric level suggest by comparison with the 7^+ and 9^- bands that the K of this band is less than 7. This assumes that the moment of inertia of the

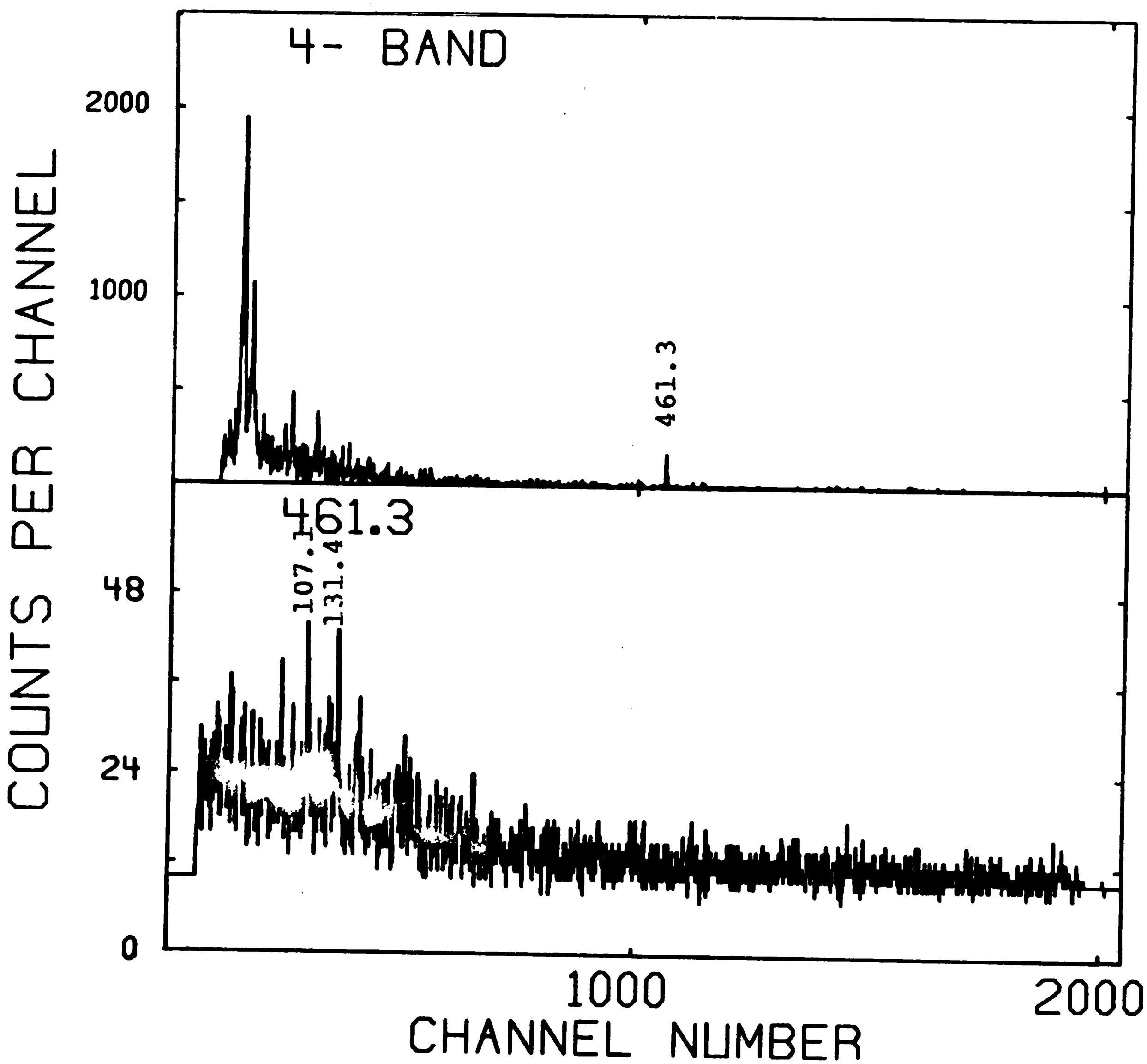

Figure 23. Delayed coincidence gates associated with the 4^- band.

nucleus does not change radically with different particle excitations, an assumption which is generally correct for highly deformed nuclei. Also the 461.3 keV γ-ray is more intense in the (p,nγ) and (p,3nγ) reactions relative to the 154.1 keV γ-ray of the 7^+ band. This might be expected if the 461.3 keV level has spin less than 7. Most of the low lying levels with spin less than 2 have been seen in the decay of ^{182}Os and no γ-rays at 461.3 keV have been reported. Therefore it is likely that the 461.3 keV level has spin between 2 and 7. The angular distribution of the 461.3 keV is nearly isotropic. This is to be expected of γ-rays deexciting long-lived states. However, Hjorth et al. measured $A_2/A_0 = 0.12 \pm 0.05$ for the transition (Hj 68). This can be compared to the value $A_2/A_0 = 0.10 \pm 0.04$ obtained here. These results are not conclusive, but if the A_2 coefficient is positive then the 461.3 keV γ-ray is not a stretched dipole transition. An E3 or M3 transition of the observed intensity of the 461.3 keV γ-ray is not likely, particularly in an odd-odd nucleus with its high level density. Therefore the 461.3 keV transition is probably quadrupole. This suggests that the 461.3 keV γ-ray deexcites a level with spin 4 if it decays to the 2^+ isomer or spin 5 if it goes to the 7^+ isomer. The primary argument for the proposed 4^- assignment is, however, entirely model dependent. The angular distributions of γ-rays from the rotational band built on the 461.3 keV level establish that the sign of δ, the mixing ratio of E2 to M1 transition amplitudes is negative. Within the Nilsson model this places restrictions on the possible assignment of the bandhead. This result will be explained in more detail in the section on g-factors.

The assignment of transitions to the rotational band built on the 2^+ isomer shown in the level scheme of Figure 11 is tentative. Only circumstantial evidence exists for the assignment of the observed rotational structure to the $2^+\{5/2^+[402\uparrow] \otimes 9/2^+[624\uparrow]\}$ configuration. The 55.6 keV $3^+\rightarrow2^+$ transition identified in the decay of ^{182}Os (Bu 73) was not found in coincidence gates set on upper members of the band, presumably because of the poor efficiency of the coincidence electronics for low energy γ-rays. The 76.3 keV transition was only clearly seen in the spectrum created by summing coincidence gates set on other members of the band. However, the transition energy, intensity, and angular distribution are consistent with its assignment to the band. As in the case of the proposed 4^- band, members of this band are seen to be more highly populated relative to the 154.1 keV $8^+\rightarrow7^+$ transition in the (p,nγ) and (p,3nγ) experiments. This, in addition to the fact that the energy spacing of the lower band levels is smaller than in the 7^+ and 9^- bands, suggests that these members have spin less than 7. No unexplained transitions of energy greater than 70 keV are seen in prompt coincidence gates set on the lower spin band members or in the spectrum created by summing delayed coincidence gates set to emphasize transitions out of an isomeric level. This implies that either the bandhead is very delayed and therefore no significant number of coincidence events occur within the range of the timing circuit, or that the transition(s) depopulating the band are of low energy and consequently detected with low efficiency and/or masked by X-rays. If the latter case obtains the low energy transition deexciting the band might feed levels which emit γ-rays which are in coincidence with members of the band. The fact that no such coincidence events were observed suggests that the first possibility mentioned above is more likely. No predictions of spin based on g-factors calculated from the Nilsson model are possible in this case because the angular distributions of members of this band are consistent with either positive or negative δ, where δ is the mixing ratio. The simplest solution consistent with the above considerations is to assign the observed rotational levels to members of the rotational band built on the 2^+, 12.7 hr isomer. This tentative assignment is made in the level scheme of Figure 11.

g-FACTORS

The magnitude of the nuclear magnetic moment can be written, apart from a spin factor, as the sum of intrinsic and collective terms:

$$\mu = I/(I + 1)\{Kg_K + g_R\} \tag{1}$$

where g_K and g_R are the intrinsic and rotational gyromagnetic ratios respectively (Ei 70). For two quasi-particle states, g_K can be written as

$$^K g_k = \Omega_1 g_{\Omega_1} \pm \Omega_2 g_{\Omega_2} \tag{2}$$

While g_R is a function of the nuclear shape and is roughly constant (∿0.3) for all rotational bands of the nucleus, g_K is determined by the intrinsic structure of the band. $(g_K - g_R)$ is therefore constant over the band and can be related within the rotational model to the mixing ratio, δ^2, of electric to magnetic transition probabilities (Al 64):

$$\frac{(g_K - g_R)^2}{Q_0{}^2} = \frac{0.871\ E_\gamma^2}{(I + 1)\ (I - 1)}\ \frac{1}{\delta^2} \tag{3}$$

where Q_0 is the intrinsic quadrupole moment determined from, for instance, Coulomb excitation studies and E_γ is the cascade transition energy in MeV.

The mixing ratio can be determined independently of a specific nuclear model from angular distribution measurements. Using the tables of Mateosian and Sunyar (Ma 74) mixing ratios of some cascade transitions in the 7^+ and 9^- bands were calculated. The experimental A_2/A_o and A_4/A_0 parameters derived from the angular distribution data differ from the theoretical coefficients by attenuation factors α_2 and α_4 respectively. These are usually related, under the assumption of a Gaussian magnetic substate population, to the single parameter σ/J where σ is the standard deviation of the Gaussian distribution and J is the spin of the initial state. The attenuation factors (and hence the value of σ/J) of a level of the rotational band can be determined from the angular distributions of the E2 crossover transitions of that same band. σ/J is not expected to vary significantly from level to level except in the case of isomeric levels for which the angular distribution of the deexciting transition is often severely attenuated. As one goes up the band σ/J should decrease slightly corresponding to the decreased attenuation. However, any decrease of σ/J for members of the 7^+ band was insignificant compared to the errors involved. Therefore an average $\sigma/J = 0.32 \pm 0.07$ was used to compute mixing ratios for levels in the 7^+ band. Table 3 lists the results of these calculations. The approximation of σ/J is probably responsible for the slight decrease of $|g_K - g_R|/Q_o$ with increasing J. Adequate angular distributions of crossover transitions in the 9^- band were not obtained, so for this band $\sigma/J = 0.32 \pm 0.07$ was used in the calculation of δ.

TABLE 3

δ AND $\frac{|g_K - g_R|}{Q_0}$ FROM ANGULAR DISTRIBUTION RESULTS AND BRANCHING RATIOS

Cascade Transition (keV)	J_i	δ_{ad}	δ_{br}		$\left(\frac{\lvert g_K - g_R\rvert}{Q_0}\right)_{ad}$	$\left(\frac{\lvert g_K - g_R\rvert}{Q_0}\right)_{br}$
154.1	8^+	0.32 ± 0.03	------------		0.056 ± 0.005	-------------
185.3	9^+	0.39 ± 0.05	------------*		0.050 ± 0.006	-------------
216.6	10^+	0.40 ± 0.06	0.42 ± 0.02		0.050 ± 0.007	0.048 ± 0.002
237.6	11^+	0.49 ± 0.07	0.42 ± 0.02		0.041 ± 0.006	0.048 ± 0.002
260.9	12^+	0.53 ± 0.11	------------*		0.038 ± 0.008	-------------
282.3	13^+	0.50 ± 0.11	0.41 ± 0.02		0.041 ± 0.009	0.050 ± 0.003
303.6	14^+	------------	0.47 ± 0.06		-------------	0.044 ± 0.006
			average	=	0.046 ± 0.007	0.048 ± 0.002
181.8	10^-	0.23 ± 0.02	------------		0.066 ± 0.005	-------------
209.3	11^-	0.32 ± 0.03	0.33 ± 0.02		0.056 ± 0.005	0.055 ± 0.004
234.9	12^-	0.35 ± 0.05	0.34 ± 0.03		0.052 ± 0.007	0.054 ± 0.005
258.9	13^-	0.30 ± 0.07	------------		0.062 ± 0.014	-------------
281.2	14^-	0.42 ± 0.11	0.34 ± 0.02		0.071 ± 0.018	0.056 ± 0.004
303.0	15^-	------------	0.36 ± 0.04		-------------	0.053 ± 0.005
			average	=	0.061 ± 0.008	0.055 ± 0.001

*The quadrupole transition needed for the calculation of δ_{br} lies in an unresolved multiplet. Its intensity cannot be determined.

Also within the rotational model, the mixing ratio can be calculated from the branching ratio, λ, of crossover-to cascade transition intensities according to (Al 64).

$$\frac{1}{\delta^2} = \frac{1}{\lambda} \frac{(E_\gamma)^5}{(E_{\gamma'})^5} \frac{(I + 1)\ (I - 1 + K)\ (I - 1 - K)}{2K^2\ (2I - 1)} - 1 \quad (4)$$

Table 3 gives values of δ and $|g_K - g_R|/Q_0$ calculated from experimental branching ratios for the 7^+ and 9^- bands. Transition intensities were obtained from γ-ray singles data taken at 125^0 with respect to the beam direction. Also for transitions in the delayed 9^- band, intensities were found from the singles spectrum created by summing the time band spectra from the "slow" timing experiment. Values of δ and $|g_K - g_R|/Q_0$, derived from these two sets of data were averaged to obtain the results listed for the 9^- band. It can be seen that the mixing ratios calculated by the two methods agree within the experimental uncertainty. Also, the branching ratio calculations indicate that $|g_K - g_R|/Q_0$, as predicted by the rotational model, is constant for each band. Furthermore, the average $|g_K - g_R|/Q_0$ determined from the angular distribution data agrees with that calculated from the branching ratios. We therefore have a more or less model independent check of the more precise branching ratio results.

The intrinsic quadrupole moment of ^{182}Re has not been measured. However, because Q_0 varies slowly over the region it is possible to use the measured Q_0 of ^{182}W, 6.4

barns with an assigned uncertainty of approximately 15% (Lo 70). The sign of $(g_K - g_R)$ is the same as that of δ derived from the angular distribution data. For the 7^+ and 9^- bands the δ's were found to be positive. Using this value of Q_0 and the average of $|g_K - g_R|/Q_0$ from the branching ratio calculation we obtain for the 7^+ band

$$g_K - g_R = 0.29 \pm 0.05. \tag{5}$$

The g-factor of the 64 hr isomer of ^{182}Re has recently been measured to be 0.399 ± 0.008 (Si 74). This can be substituted into Equation (1) for the magnetic moment. With the assumption of $K = 7$ for the ground band, Equations (1) and (5) can be solved simultaneously for g_K and g_R. This gives $g_K = 0.44 \pm 0.02$ and $g_R = 0.15 \pm 0.07$. g_R is significantly lower than the expected ~ 0.3, although values this low have been found in ^{161}Dy and ^{177}Hf (Hu 69). An incorrect K assignment for the band built on the 64 hr isomer would not alter this result. It is clear that the 64 hr isomer has at least spin 6, and for high K, μ (see Equation (1)) and hence g_K is insensitive to g_R. g_K is, in effect, determined by Equation (1) for high K and g_R is subsequently fixed by Equation (5). g_K can be determined independently from Equation (2) and empirical g_Ω of neighboring odd mass nuclei (Kh 74) for the $5/2^+[402\uparrow]$ proton and the $9/2^+[624\uparrow]$ neutron. This calculation gives $g_K = 0.43$ in agreement with the experimental result. One possible explanation for the unusually small value obtained for g_R is that the Q_0 of ^{182}Re is much smaller than that obtained for neighboring deformed nuclei. It is clear, however, that either g_R or Q_0 deviates substantially from the anticipated value.

The small value of g_R for ^{182}Re obtained here might be expected on the basis of partially confirmed calculations of g_R for several nearby odd-mass nuclei performed by Prior et al. (Pr 68). These researchers predict that ^{179}Hf and ^{181}W have g_R values of 0.14 (or 0.12) and 0.05 respectively. The reduction in g_R as compared to that of other odd-mass nuclei is attributed by Prior et al. to the influence of the outer shell nucleons, in this case the $9/2^+[624\uparrow]$ neutron. These results can provide a possible explanation of the relatively small value of g_R obtained for ^{182}Re. This is because the moment of inertia, I, can be written as the sum of the moment of inertia of the protons in the nucleus, I_p, and that of the neutrons, I_n:

$$I = I_p + I_n \tag{6}$$

Furthermore, one can write

$$g_R = \frac{I_p}{I} = \frac{I_p}{I_p + I_n} \quad \text{(Sh 74, p. 436)} \tag{7}$$

Generally, both I_p and I_n of an odd-odd nucleus will be greater than the corresponding values for the nucleus comprised of one less proton and one less neutron. However by comparing the values of $\hbar^2/2I$ of ^{181}W, ^{181}Re, and ^{182}Re (estimated from the energy difference of the first two excited levels of the ground bands) one finds that the odd proton of ^{182}Re does little to increase the I_p of ^{182}Re over that of ^{181}W while the odd neutron apparently drastically increases the I_n of ^{182}Re over that of ^{181}Re. Thus, according to the above equations, one would expect that the g_R of ^{182}Re would be smaller than that of ^{181}Re and close to the ^{181}W value. The predictions of Prior et al. for ^{181}W have not been tested experimentally. However, similar predictions for ^{167}Er and ^{161}Dy have been confirmed (Pr 68).

Table 4 lists theoretical values of g_K calculated in the asymptotic limit of the deformation parameters compared to experimental g_K obtained from branching ratios of the 7^+ and 9^- bands. Q_0 was assumed to be 6.4 barns and g_R was taken to be 0.15. Although the theoretical calculation was carried out in the asymptotic limit of deformation, no significant changes are introduced when the Nilsson wave functions for a deformation appropriate to ^{182}Re are used (Ni 55). It can be seen that the experimental g_K is consistent with the $9^-\{9/2^-[514\uparrow] \blacksquare\ 9/2^+[624\uparrow]\}$ assignment.

If the validity of the rotational model is assumed and g_R and Q_0 are known, then g_K can be calculated from the experimental mixing ratio δ. This experimental g_K can be compared to theoretical predictions thereby serving as an aid in identifying the band structure. Unfortunately, branching ratios were not obtained for the proposed 2^+ and 4^- bands, and the angular distribution results were

TABLE 4

THEORETICAL AND EXPERIMENTAL g_K

Proton	Neutron	K	Theoretical[1] g_K	Experimental[2] g_K, 7^+ Band	Experimental[2] g_K, 9^- Band
$5/2^+[402\uparrow]$	$9/2^+[624\uparrow]$	7	0.39	0.44	0.63
$5/2^+[402\uparrow]$	$7/2^-[514\downarrow]$	6	0.96	0.50	0.74
$9/2^-[514\uparrow]$	$9/2^+[624\uparrow]$	9	0.52	0.37	0.50
$7/2^+[404\downarrow]$	$9/2^+[624\uparrow]$	8	0.03	0.39	0.55
$5/2^+[402\uparrow]$	$5/2^-[512\uparrow]$	5	1.15	0.60	0.88
$5/2^+[402\uparrow]$	$7/2^+[633\uparrow]$	6	0.42	0.50	0.74

[1]Calculated from the asymptotic expression

$$g_K = 1/K\,(g_{sn}\,\Sigma_n + g_{\ell n}\Lambda_n) \pm (g_{sp}\Sigma_p + g_{\ell p}\Lambda_p)$$

[2]Calculated from γ-ray branching ratios according to Equations (3) and (4) assuming $Q_0 = 6.4$ barns, $g_R = 0.15$, $g_{s,eff} = 0.8\ g_{s,free}$.

insufficient to determine δ. However, the angular distributions of the cascade transitions of the proposed 4^- band establish that the sign of δ and hence, the sign of $(g_K - g_R)$ is negative. Therefore $g_K<g_R$, a requirement which limits the possible assignments for the bandhead. Table 5 lists theoretical values of g_K calculated for two-quasiparticle states in ^{182}Re expected at low excitation energy. For each particle coupling the triplet state, predicted by Gallagher and Moszkowski to have the lower energy, is listed first, followed by the singlet state. It can be seen that only three K = 1 states, the K = 4 or 5 states from the $\{1/2^-[541\downarrow] \otimes 9/2^+[624\uparrow]\}$ configuration and the K = 8 state from the singlet coupling $\{7/2^+[404\downarrow] \otimes 9/2^+[624\uparrow]\}$ are consistent with $g_K \leq 0.3$. For reasons already explained it is unlikely that the 461.3 keV isomeric level has spin as high as 8 or as low as 1. Furthermore, the triplet 4^- state is expected to be found at a lower excitation energy than the singlet 5^- state. Therefore we tentatively assign the 461.3 keV bandhead to the $4^-\{1/2^-[541\downarrow] \otimes 9/2^+[624\uparrow]\}$ configuration.

TABLE 5

THEORETICAL g_K

Particle Proton	Particle Neutron	K (lower state) (higher state)	Theoretical (1) g_K
$5/2^+[402\uparrow]$	$9/2^+[624\uparrow]$	7	0.39
		2	-2.88
$5/2^+[402\uparrow]$	$7/2^-[514\downarrow]$	1	-5.76
		6	0.96
$9/2^-[514\uparrow]$	$9/2^+[624\uparrow]$	9	0.52
		0	
$7/2^+[404\downarrow]$	$9/2^+[624\uparrow]$	1	-3.29
		8	0.03
$1/2^-[541\downarrow]$	$9/2^+[624\uparrow]$	4	-0.07
		5	-0.55
$5/2^+[402\uparrow]$	$1/2^-[510\uparrow]$	3	0.90
		2	2.88
$5/2^+[402\uparrow]$	$5/2^-[512\uparrow]$	5	1.15
		0	
$5/2^+[402\uparrow]$	$1/2^-[521\downarrow]$	2	1.35
		3	1.92
$5/2^+[402\uparrow]$	$7/2^+[633\uparrow]$	6	0.45
		1	-5.77

[1]From the asymptotic expression (with $g_{s,\,eff} = 0.8\, g_{s,\,free}$)

$$g_K = 1/K\{(g_{sp}\Sigma_p + g_{\ell p}\Lambda_p) \pm (g_{sn}\Sigma_n + g_{\ell n}\Lambda_n)\} .$$

CONCLUSION

The results reported in this thesis for states in ^{182}Re constitute a substantial improvement over those previously published. Knowledge of the 7^+ and 9^- bands have been extended to higher spin levels. Particularly interesting is the observation of the isomeric level at 2256.4 keV which feeds into the 9^- band. Because of the high K of this level, a study of collective states built on this configuration should prove fruitful. An aid to this study would be the experimental determination of the g-factor for this state. This should be feasible since the transitions deexciting the 2256.4 keV level are not severely attenuated.

The 2^+ and 4^- bands as reported here have not been previously observed. While there is little doubt that these bands do indeed belong to ^{182}Re, the particular assignments given are tentative. Further study is required for more definite assignments. However, for reasons noted above this will probably prove quite difficult to accomplish.

The most interesting result of this study is the unusually small value of g_R obtained for the 7^+ band. Some theoretical support for this result has been given. However, much more work is needed.

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