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R. W. Hoff
Lawrence Livermore National Laboratory
Livermore, California

J. Kern
Institut de Physique de l'Universite
Fribourg, Suisse

R. Piepenbring and J. P. Boisson
Institut des Sciences Nucleaires
Universite de Grenoble, Grenoble, France

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R. W. Hoff
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ABSTRACT

A technique for modeling quasiparticle excitation energies and rotational parameters in odd-odd deformed nuclei has been applied to actinide species where new experimental data have been obtained by use of neutron-capture gamma-ray spectroscopy. The input parameters required for the calculation were derived from empirical data on single-particle excitations in neighboring odd-mass nuclei. Calculated configuration-specific values for the Gallagher-Moszkowski splittings were used. Calculated and experimental level structures for ^{238}Np, ^{244}Am, and ^{250}Bk are compared, as well as those for several nuclei in the rare-earth region. The agreement for the actinide species is excellent, with bandhead energies deviating 22 keV and rotational parameters 5%, on the average. Corresponding average deviations for five rare-earth nuclei are 47 keV and 7%. Several applications of this modeling technique are discussed.

The method used in this paper to model the level structure of odd-odd deformed nuclei is based upon a technique first described in papers by Struble et al.[1] and Motz et al.[2] They proposed that if the p-n residual interaction energy is small compared with the energy with which the odd nucleons are bound to the core, the excitation can be calculated by a simple extension of the odd-A model and the interaction energy can be treated later as a perturbation. Thus, the model can be described in terms of two simple concepts. The first is that in considering the coupling of two unpaired particles to a deformed core, the excitation energy of a given configuration can be described as the sum of each of the odd-nucleon excitations. The second concept is that the effective moment of inertia for a rotational band can be expressed as the sum of three components: the moment of inertia of the even-even core plus increments from the addition of each of the odd nucleons.

The excitation of an odd nucleon in a deformed nucleus can be treated theoretically by various versions of single-particle potential theory. For the purposes of this paper, however, the excitations are obtained from experimental data for neighboring odd-mass nuclei. In the actinide region, these data have been systematically surveyed by Chasman et al.[3] The quasiparticle energy E_{qp} for a given orbital in an odd-mass nucleus can be found from the expression

$$E_I = E_{qp} + h^2/2q[I(I+1)-K^2+d_{K,1/2}\, a(I+1/2)(-1)^{I+1/2}] \quad (1)$$

where a is the decoupling parameter. The term $-K^2$ was assumed in this expression instead of the often-used form that contains a $-2K^2$ term. This modification has the effect of changing the magnitude (and even the sign) of the zero-point rotational energy E_{ZPR} for a given band. The quantity E_{ZPR} is the difference between E_K (defined by substituting K for I in Eq. 1), and E_{qp}. Thus, it can be expressed as

$$E_{ZPR} = h^2/2q(K - ad_{K,1/2}). \quad (2)$$

A more precise definition of E_{ZPR} includes a term containing $\langle j^2 \rangle$, which is usually the major contributor and which consequently yields a larger zero-point energy than that given by Eq. 2. Nevertheless, several authors have chosen to incorporate this term in the expression E_{qp} and to evaluate E_{ZPR} using a simple expression, that given by Eq. 2. For example, Ogle et al.[4] adopted the use of a $-K^2$ term (as in Eq. 1) for their data analysis. They concluded that if one were to consider increasing the coefficient of this term, it could not be chosen much larger than 1.5 without destroying the qualitative agreement between Nilsson model predictions and quasiparticle level systematics.

The effective moment of inertia for a given rotational band, q, is derived by the following method:

$$q_{odd\text{-}odd} = q_{even\text{-}even} + dq_p + dq_n$$

$$= q_{e\text{-}e} + (q_p - q_{e\text{-}e}) + (q_n - q_{e\text{-}e})$$

$$= q_p + q_n - q_{e\text{-}e}. \qquad (3)$$

where q_p and q_n are the moments of inertia for the relevant rotational band in the neighboring odd mass nuclei and dq_p and dq_n are the increments to $q_{even\text{-}even}$ due to the unpaired proton and neutron. In the model being discussed here, effects due to Coriolis mixing that are explicit to odd-odd nuclei are not included. On the other hand, those experimentally-observed manifestations of Coriolis mixing in odd-A nuclei such as the compression or expansion of rotational spacing within a given band are included in the calculated effective moment of inertia for the odd-odd nucleus.

The excitation energies of levels in the odd-odd nucleus are calculated using the expression

$$E_I = E^p{}_{qp} + E^n{}_{qp} + h^2/2q_{odd\text{-}odd}\,[I(I+1)-K^2] + (1/2-d_{S,0})E_{GM}$$

$$- d_{K,0}(-1)^I E_N p \qquad (4)$$

where p denotes the parity of the states as introduced in Ref. 5 and is equal to ± 1 for positive or negative parity. The results from this calculation are completely predictive. No experimental information from the odd-odd nucleus itself is included, only empirical data derived from neighboring odd-mass and even-even nuclei.

The E_{GM} and E_N terms in Eq. 4, which are designated as the

Gallagher-Moszkowski splitting[6] and Newby shift[7], respectively, are functions of the effective neutron-proton residual interaction. For the calculated Gallagher-Moszkowski splittings and Newby shifts reported in this paper, a zero-range central (d) force between proton and neutron and a harmonic-oscillator central potential were assumed. (For a detailed discussion of the method, see Ref. 5). The one adjustable parameter needed to describe the strength of the d force obtained from a global fit of G-M splittings in the actinide region, specifically the experimental values for the 12 configuration pairs shown in Figure 1. Calculated and experimental E_{GM} and E_N values are listed in Table 1.

In a few instances in Table 1, experimental data are reported for configurations occurring in more than one nuclide. Such an example is given in Fig. 2 which shows the excited levels of a K=0 band in ^{238}Np, ^{240}Am, ^{242}Am, and ^{244}Am. It can be seen that the level spacings within the band are very similar among these nuclei. The experimental and calculated bandhead energies and rotational parameters for each nucleus also show reasonably good agreement. On the other hand, the calculated matrix elements for the G-M splittings and Newby terms do not reproduce experiment. Of the 15 separate configurations for which E_{GM} values are listed in Table 1, only in three cases do the calculated and experimental values show significant disagreement, i.e. the ratios fall outside the range $0.65 < E_{GM}(\text{exp/calc}) < 1.39$.

Several authors have published calculations of G M splittings and Newby shifts made assuming simple central forces.[8] Boisson et al.[5] have worked with empirical data from rare-earth nuclei involving an initial sample of E_{GM} matrix elements for 43 two-quasiparticle configurations that was reduced to 23 empirical values of greatest reliability. They determined parameters for several forms of an assumed central-force effective interaction by fitting the calculated matrix elements to the empirical data. Sood and Singh[9] have calculated E_{GM} matrix elements for configuration pairs in the nuclei ^{238}Np, ^{244}Am, and ^{250}Bk with a zero-range proton-neutron residual interaction. For the adjustable parameter that determines the strength of the interaction, they have chosen to adopt a different value for each nucleus; the value is usually adjusted to reproduce the G-M splitting that includes the ground state rotational band. For the 9 G-M splittings in these nuclei where comparison can made with experiment, their calculations show approximately the same level of agreement as for those listed in Table 1. If one replots the data of Fig.1 as a function of mass number, however, it appears there is no obvious trend, which weakens the case for adjusting the residual interaction strength for each nucleus.

Comparisons between the experimental and calculated band-head energies and rotational parameters of ^{244}Am and ^{250}Bk are shown in Tables 2 and 3 and in Fig. 3. The calculated level energies, which have obtained using Eq. 2, are given a zero-energy adjustment so that the calculated and experimental ground state energies match. The experimental data for these nuclei include information from recent measurements using the (n,g) and (d,p) reactions[10,11], as well as data from earlier measurements[12,13]. The information on the level schemes of neighboring nuclei was taken largely from the Table of Isotopes[13]. The uncertainties on band-head energy listed in the fourth columns of Tables 2 and 3 do not represent experimental error, but rather are derived from the spread in the two experimental values taken from the odd-mass nuclei. For example, the excitation of a given proton orbital in ^{250}Bk, relative to the ground-state orbital, is derived from observations in ^{249}Bk and ^{251}Bk. The two experimental observations are averaged and their spread (plus that from the odd-neutron observations) determines the uncertainties listed.

The agreement between experimental and calculated band-head energies for these nuclides is excellent; the average deviations are $\pm$19 keV and $\pm$17 keV for ^{244}Am and ^{250}Bk, respectively. Similarly, the experimental rotational parameters agree extremely well with the calculated values; the average deviations are $\pm$7% and $\pm$5% for ^{244}Am and ^{250}Bk, respectively. This ability to predict rotational parameters proves to be useful in identifying the configuration of a rotational band. One can see in ^{250}Bk, for example, that there is a clear differentiation between configurations that contain the $3/2^-$[521]p orbital and those that contain the $7/2^+$[633]p orbital. For the former, the calculated rotational parameters have values of 5.7-5.8 keV. For the latter, where the proton orbital is subject to strong

Coriolis interaction, the calculated values are smaller, 4.4-4.5 keV in several cases and even 3.3 keV when this proton is coupled with a $1/2^-$[761] neutron.

In Table 4 the results of the comparisons are summarized for ^{250}Bk and ^{244}Am, along with data[14] for ^{238}Np, and for several rare-earth nuclides. For this latter set, the modeling techniques used was nearly identical to that for the actinides; one difference was that values for E_{GM} and E_N were obtained from ref. 5 where these matrix elements were calculated employing a more complex force, namely, a central force with intrinsic-spin polarization and with long-range and tensor contributions which were determined from a fit to experimental data.

Thus, the evidence shows this modeling technique accurately reproduces experimental band-head energies and rotational parameters for these deformed nuclei. With this method, then, one can model all of the intrinsic single-particle excitations and rotational bands built on these excitations in any deformed odd-odd species where input data are available. This includes a capability to model structure in some odd-odd nuclei for which little or no experimental data exist. Calculated level schemes can be extended to energies somewhat higher than the ranges given in Table 4, although it must be recognized that other kinds of excitations in these nuclei, e.g. vibrational motion and quasiparticle excitations involving more than two unpaired nuclei, are neglected in this limited approach.

Several applications of this modeling technique have proven to be useful. For example, an average resonance capture measurement[15] populating levels in ^{176}Lu has been performed using the filtered neutron beams available at the Brookhaven High Flux Beam Reactor. In this study, a complete set of $J^P=2^- - 5^-$ levels up to an excitation of 1100 keV has been reported. A comparison of the cumulative number of levels in this spin and parity range obtained from the experiment with a corresponding calculated set shows that they are in generally good agreement (see Fig. 4). The comparison involves a total of 40 predicted rotational bands.

In another paper[16], existing experimental data for ^{242}U beta decay which were measured by Haustein et al.[17] were given a new interpretation with the aid of the phenomenological model of this paper and by comparison with recent experimental data[10] for the levels of ^{244}Am. There has been developed an experimentally-based level scheme for ^{242}Np (see Fig. 5) in which all predicted I=1 levels up to 585 keV have been identified and are being populated by ^{242}U beta decay. For the two lowest-lying K=1 bands, both I=1 and I=2 levels have been assigned. The agreement for the bandhead energies and rotational spacings of these bands in ^{242}Np and ^{244}Am is excellent. This behavior can be understood in terms of the near degeneracy of the $5/2^+[642]$ and $5/2^-[523]$ proton orbitals in these nuclei.

A final example of application of the model involves the calculation of cross-section ratios for the production of isomers in neutron-induced reactions, both capture and (n,2n), where the product nuclei are odd-odd deformed species. It has been found that the hundreds of discrete levels and their gamma-ray branching ratios provided by the modeling are necessary in order to achieve agreement between calculation and experiment. A more complete description of this is given in another paper[18] submitted to this conference.

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Table I. Comparison of experimental and calculated E(GM) and E(N) values for configurations in some actinide nuclei.

Proton Config.	Neutron Config.	Nucleus	E(GM/N)[a] (keV)		
			Exp.	Calc.	Exp/Calc
1/2-[530]	7/2-[743]	234Pa	77.5	117.	0.67
	1/2+[631]	234Pa	N-46.8	-44.2	1.06
		236Pa	N-50.2	-44.2	1.14
		238Np	N-37.9	-43.1	0.88
5/2+[642]	1/2+[631]	238Np	82.4	70.	1.18
5/2-[523]	1/2-[501]	242Am	39.	44.	0.89
	1/2+[631]	238Np	52.2	60.	0.87
		242Am	52.1	61.	0.85
		244Am	70.	61.	1.15
	1/2+[620]	242Am	21.	116.	0.18
		244Am	16.	116.	0.14
	5/2+[622]	238Np	1.	95.	0.01
		240Am	10.	96.	0.10
		242Am	5.	96.	0.05
		238Np	N+27.	-15.2	-1.78
		240Am	N+28.	-14.7	-1.90
		242Am	N+27.3	-14.6	-1.87
		244Am	N+25.7	-14.6	-1.76
	7/2+[624]	244Am	200.2	208.	0.96
3/2-[521]	9/2-[734]	248Bk	186.5	134.	1.39
	7/2+[613]	250Bk	66.4	60.	1.11
	1/2+[620]	250Bk	110.3	115.	0.96
7/2+[633]	7/2+[624]	244Am	N+33.1		
	9/2-[734]	248Bk	122.	189.	0.65
	7/2+[613]	250Bk	135.0	47.	2.87
		250Bk	N-25.0	-58.0	0.43
	1/2+[620]	250Bk	83.1	60.	1.39
	3/2+[622]	250Bk	91.2	69.	1.32
	1/2-[761]	250Bk	38.		

a - The values listed below are Gallagher-Moszkowski matrix elements except when indicated as a Newby term by an N in col. 4.

Table 2. Comparison of experimental and predicted band-head energies and rotational parameters for ^{244}Am

K	Configuration	Band Head Energy Exp. (keV)	Band Head Energy Calc. (keV)	Rot. Par. A Exp. (keV)	Rot. Par. A Calc. (keV)
1+	§5/2+[642]p - 7/2+[624]nt	85	60+-42	3.4	3.0
1-	§5/2-[523]p - 7/2+[624]nt	173	161+-14	5.3	5.4
2-	§3/2-[521]p - 7/2+[624]nt	259	235+-56	5.8	5.8
0-	§5/2-[523]p - 5/2+[622]nt	286(1-)	319+-31(1-)	5.3	5.4
3+	§1/2+[400]p - 7/2+[624]nt	345	(336)	5.2	(5.4)
0+	§7/2+[633]p - 7/2+[624]nt	374(0+)	362+-69(0+)	6.0	6.9
2+	§5/2+[642]p - 1/2+[631]nt	(416)	451+-56	(2.7)	3.1
2+	§5/2-[523]p - 9/2-[734]nt	417	426+-21	4.1	4.2
3-	§5/2-[523]p + 1/2+[631]nt	418	442+-28	(5.6)	5.7
0+	§5/2+[642]p - 5/2+[622]nt	(475)(2+)	463+-59(2+)	--	3.0
2-	§5/2-[523]p - 1/2+[631]nt	482	488+-28	(6.6)	5.7
2-	§5/2+[642]p - 9/2-[734]nt	514	538+-49	3.2	2.6
2+	§3/2+[651]p - 7/2+[624]nt	(612)	(395)	(5.8)	(6.2)
1+	§5/2-[523]p - 7/2-[743]nt	(668)	665+-14	--	5.8
1-	§3/2-[521]p - 5/2+[622]nt	678	586+-74	5.1	5.7
1-	§5/2+[642]p - 7/2-[743]nt		826+-42		3.1
Average deviations:		19 (for 9 bands)		0.28(5.4%) (for 9 bands)	

Table 3. Comparison of experimental and predicted band-head energies and rotational parameters for ^{250}Bk

K	Configuration	Band Head Energy Exp. (keV)	Band Head Energy Calc. (keV)	Rot. Par. A Exp. (keV)	Rot. Par. A Calc. (keV)
2-	§3/2-[521]p + 1/2+[620]n†	0	0	5.77	5.70
1-	§3/2-[521]p - 1/2+[620]n†	104	99+-4	5.35	5.70
4+	§7/2+[633]p + 1/2+[620]n†	36	37+-18	4.31	4.37
3+	§7/2+[633†p - 1/2+[620]n†	115	88+-18	4.14	4.37
5-	§3/2-[521]p + 7/2+[613]n†	97	100+-33	5.80	5.83
2-	§3/2-[521]p - 7/2+[613]n†	146	137+-33	5.59	5.83
7+	§7/2+[633†p + 7/2+[613]n†	86	114+-47	4.56	4.44
0+	§7/2+[633]p - 7/2+[613]n†	175(I+)	110+-47(1+)	--	4.44
2+	§7/2+[633]p - 3/2+[622]n†	212	211+-33	4.18	4.50
5+	§7/2+[633]p + 3/2+[622]n†	316	287+-33	4.43	4.50
6+	§5/2+[642]p + 7/2+[613]n†	406	410+-89	--	5.39
3-	§7/2+[633]p - 1/2-[761]n†	526	513+-18	3.4	3.30
4-	§7/2+[633]p + 1/2-[761]n†	566	596+-18	3.9	3.30
6+	§7/2+[633]p + 5/2+[622]n†	552	557+-25	--	4.41
Average deviations:		17 (for 13 bands)		0.20(4.7%) (for 11 bands)	

Table 4. Odd-odd nuclei in actinide and rare-earth regions: Comparison of experimental and calculated bandhead energies, rotational parameters, and G-M splittings.

Nucleus	Number of bands	Energy range (keV)	$\langle E_{exp}-E_{calc} \rangle$ (keV)	$\langle A_{exp}-A_{calc} \rangle$ (keV)	E_{GM} exp/calc
^{238}Np	9	0 - 345	29	0.14 (3.2%)	1.18,0.87
^{244}Am	16	0 - 680	19	0.28 (7.4%)	1.15,0.14,0.96
^{250}Bk	14	0 - 570	17	0.20 (4.7%)	1.11,0.96,2.87, 1.39,1.32
^{160}Tb	8	0 - 380	41	0.61 (8.1%)	1.03,1.07,1.13
^{166}Ho	10	0 - 560	47	0.74 (8.7%)	0.80,1.08,1.31
^{170}Tm	5	0 - 450	63	0.46 (5.2%)	2.04,0.98
^{176}Lu	12	0 - 840	58	1.0 (9.2%)	1.14,0.48,1.01, 0.91,0.39
^{182}Ta	7	0 - 270	24	0.47 (3.9%)	0.94,0.97,1.14

FIGURE CAPTIONS

1. Comparison of experimental and calculated Gallagher-Moszkowski matrix elements for several configuration pairs in odd-odd actinide nuclei.

2. Excited levels of the $5/2^-[523]p - 5/2^+[622]n$ rotational band in four actinide nuclei. Experimental and calculated values of the energy of the I=1 bandhead level(E_1), rotational parameter(A), Newby term(E_N), and Gallagher-Moszkowski splitting(E_{GM}) are compared.

3. Experimental and calculated levels in ^{250}Bk. Thirty-seven levels, comprising 14 rotational bands, are shown.

4. Comparison of experimental level structure data for ^{176}Lu from average resonance capture measurements with model calculation. Cumulative level number histograms for all states with spins $2^-,3^-,4^-,5^-$(left), $3^-,4^-$(center), and $2^-,5^-$(right). The cross-hatched regions show the range of the maximum and minimum numbers of states deduced from the ARC data. The thick dashed lines are the model calculations.

5. Comparison of the newly-interpreted ^{242}Np level scheme with that predicted in a model calculation and with an experimental ^{244}Am level scheme. A key to notation for configuration assignments is shown in the figure. The present interpretation indicates that all levels shown for ^{242}Np are bandheads except for the I=2 levels at 12.0 and 89.2 keV.

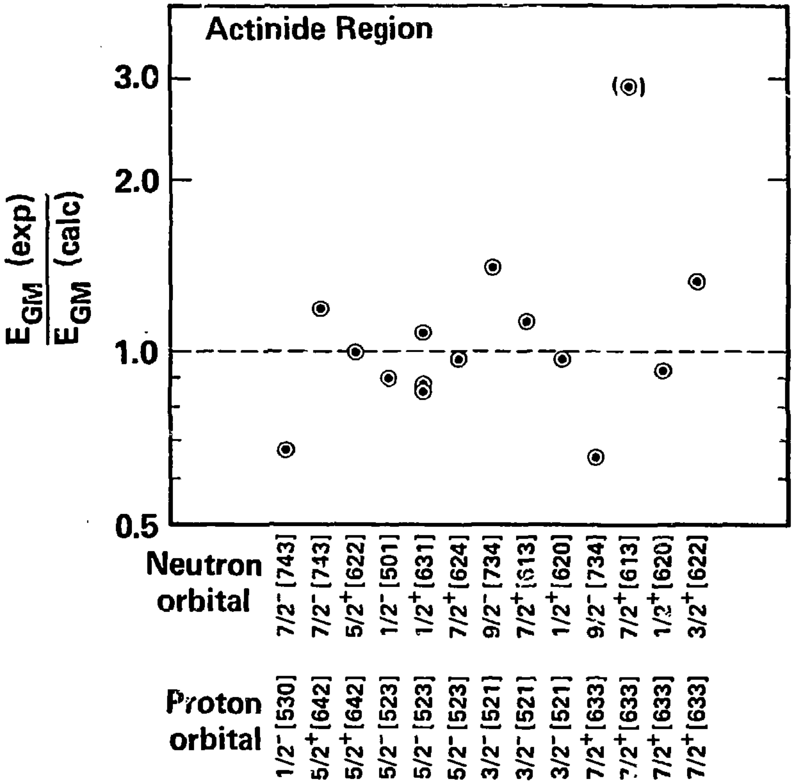
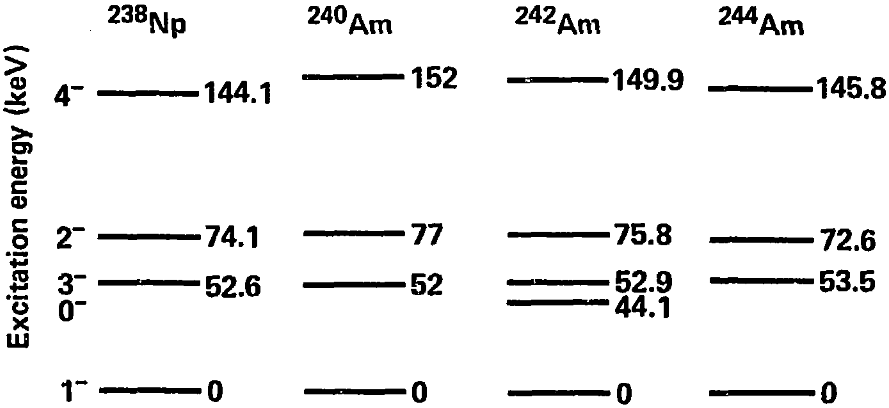

Actinide Region
3.0
2.0
1.0
0.5
E_{GM} (exp) / E_{GM} (calc)
Neutron orbital
7/2⁻[743] 7/2⁻[743] 5/2⁺[622] 1/2⁻[501] 1/2⁺[631] 7/2⁺[624] 9/2⁻[734] 7/2⁺[613] 1/2⁺[620] 9/2⁻[734] 7/2⁺[613] 1/2⁺[620] 3/2⁺[622]
Proton orbital
1/2⁻[530] 5/2⁺[642] 5/2⁺[642] 5/2⁻[523] 5/2⁻[523] 5/2⁻[523] 3/2⁻[521] 3/2⁻[521] 3/2⁻[521] 7/2⁺[633] 7/2⁺[633] 7/2⁺[633] 7/2⁺[633]

Figure 1.



		^{238}Np	^{240}Am	^{242}Am	^{244}Am
E_1 (keV)	– exp	299	346	0	286.2
	– calc	279	264	0	315
A(keV)	– exp	5.1	5.4	5.29	5.29
	– calc	5.4	5.3	5.11	5.35
E_N (keV)	– exp	+26.9	+28	+27.3	+25.4
	– calc	–15.2	–14.7	–14.6	–14.6
E_{GM} (keV)	– exp	1	10	5	–
	– calc	95	96	96	96

Figure 2.

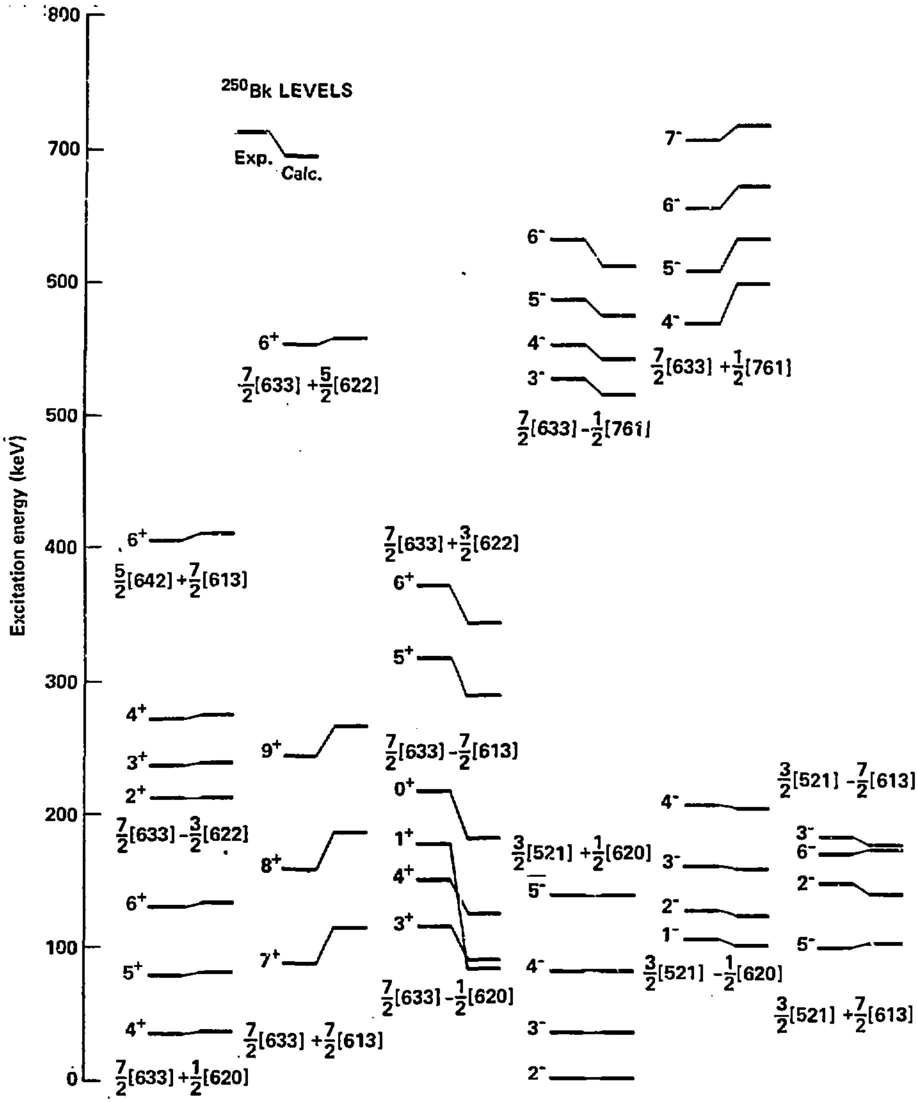
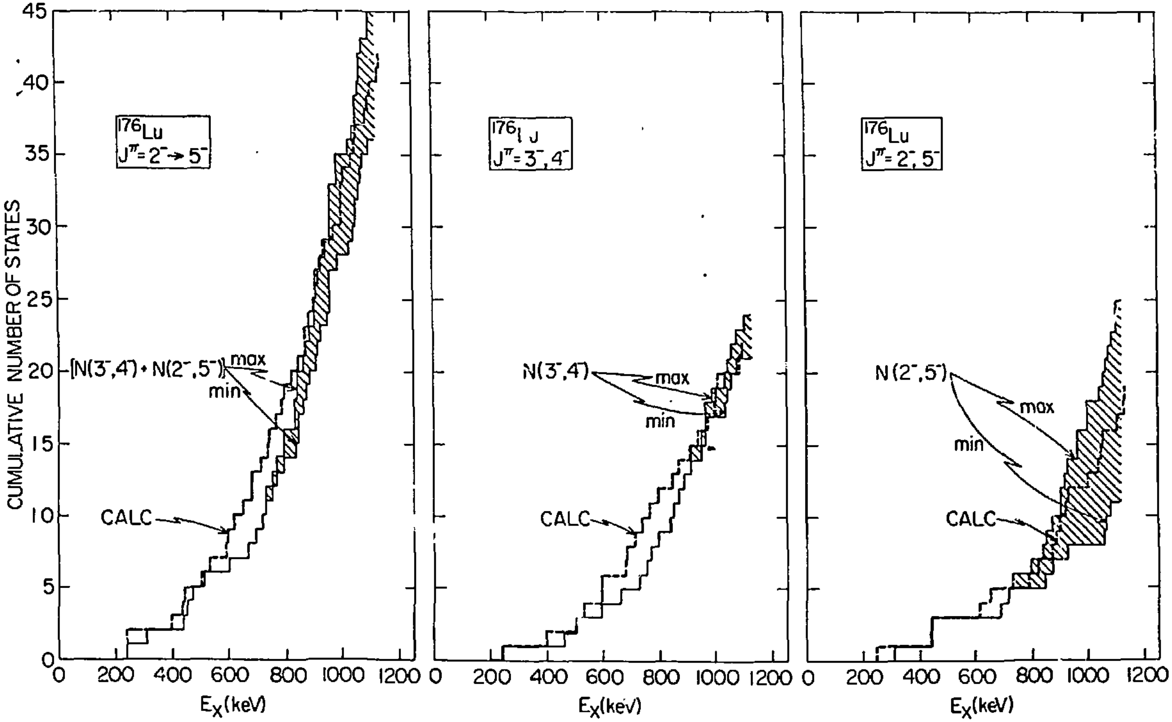
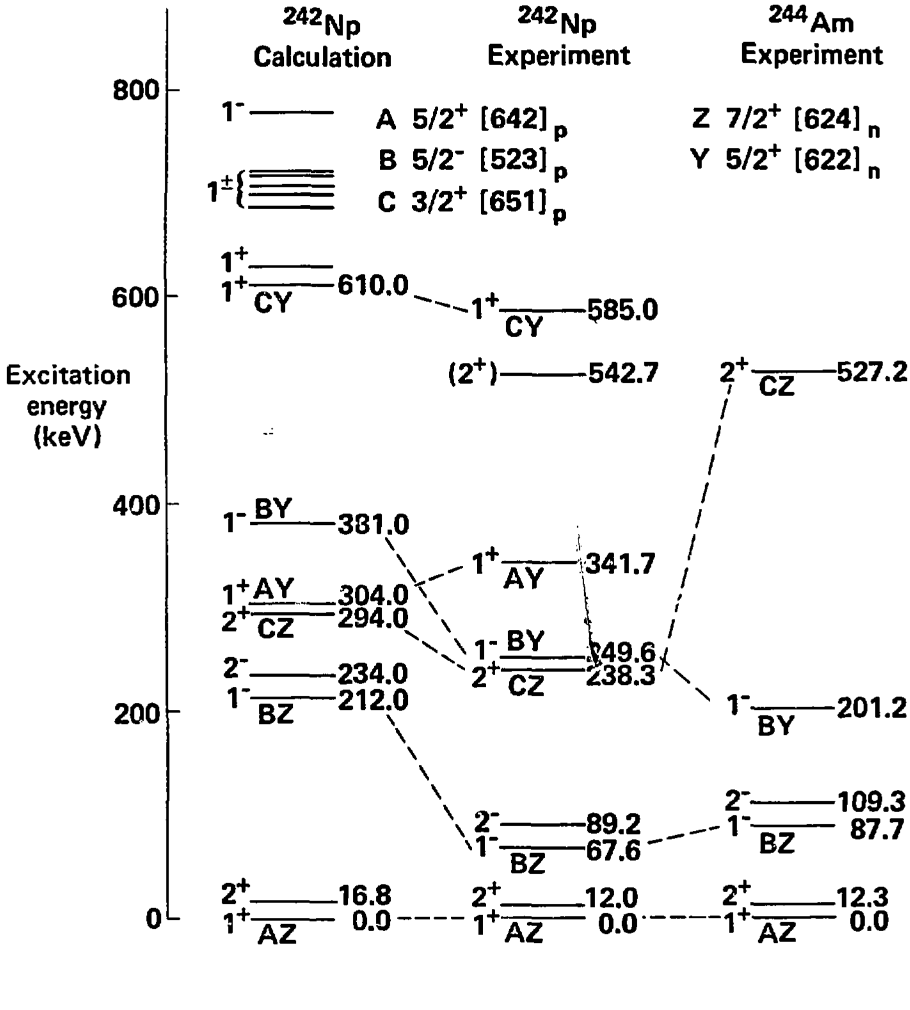

250Bk LEVELS
Exp.
Calc.
Excitation energy (keV)
800
700
600
500
400
300
200
100
0
7/2[633]+1/2[620]
7/2[633]+7/2[613]
7/2[633]-1/2[620]
7/2[633]-3/2[622]
5/2[642]+7/2[613]
7/2[633]+5/2[622]
7/2[633]-7/2[613]
7/2[633]+3/2[622]
7/2[633]-1/2[761]
7/2[633]+1/2[761]
3/2[521]+1/2[620]
3/2[521]-1/2[620]
3/2[521]-7/2[613]
3/2[521]+7/2[613]

Figure 3.



CUMULATIVE NUMBER OF STATES
^{176}Lu
$J^{\pi}=2^{-}\rightarrow 5^{-}$
[N(3⁻,4⁻)+N(2⁻,5⁻)]
max
min
CALC
^{176}Lu
$J^{\pi}=3^{-},4^{-}$
N(3⁻,4⁻)
max
min
CALC
^{176}Lu
$J^{\pi}=2^{-},5^{-}$
N(2⁻,5⁻)
max
min
CALC
E_X(keV)
E_X(keV)
E_X(keV)

Figure 4.



242Np Calculation
242Np Experiment
244Am Experiment
800
600
400
200
0
Excitation energy (keV)
A 5/2+ [642]p
B 5/2- [523]p
C 3/2+ [651]p
Z 7/2+ [624]n
Y 5/2+ [622]n
1-
1±
1+
1+ CY 610.0
1+ CY 585.0
(2+) 542.7
2+ CZ 527.2
1- BY 381.0
1+ AY 341.7
1+ AY 304.0
2+ CZ 294.0
1- BY 249.6
2+ CZ 238.3
2- 234.0
1- BZ 212.0
1- BY 201.2
2- 109.3
2- 89.2
1- BZ 87.7
1- BZ 67.6
2+ 16.8
2+ 12.0
2+ 12.3
1+ AZ 0.0
1+ AZ 0.0
1+ AZ 0.0

Figure 5.