GENERAL POLICIES - Presentation of Data

The Nuclear Data Sheets are prepared from the Evaluated Nuclear Structure Data File (ENSDF), a computer file maintained by the National Nuclear Data Center on behalf of the International Network for Nuclear Structure and Decay Data Evaluations. See page iii for a list of the members of this network and their evaluation responsibilities. The presentation of material in the Nuclear Data Sheets reflects the organization of ENSDF, which is a collection of "data sets". For each nuclear species, these data sets present the following types of information:

- The adopted properties of the nucleus.
- The evaluated results of a single type of experiment, such as a radioactive decay, a single nuclear reaction, or the combined results of a number of similar types of experiments, such as (HI,xnγ) reactions. The data given in ENSDF are primarily derived from experimental information.

The general policies and conventions followed in the preparation of these data sets and in the presentation of material in the Nuclear Data Sheets (NDS) are discussed below.

General

The following policies apply to the adoption or presentation of data. Deviations from these policies will be noted by the evaluator.

1. The excitation energies of levels connected by γ transitions are from a least-squares fit to the adopted γ energies.

2. Dominant decay branches (*i.e.*, for the decay of ground states and isomeric states) are rounded off to 100 when the competing branches total less than approximately 0.001%. When only one branch has been observed and no estimate can be made for expected competing branches, the observed branch is given as $\leq$100 and the competing branch(es) as "%branching=?".

3. Total internal-conversion coefficients (α) for each transition are theoretical values corresponding to the listed radiation character (*i.e.*, multipolarity) and mixing ratio (δ). For a transition of mixed character (two or more multipolarities) and unknown mixing ratio, α is the average of the possible extremes and the uncertainty overlaps the full range of values.

   In all calculations by the evaluator involving internal-conversion coefficients, a 1.4% uncertainty is assumed for the theoretical coefficients.

4. The cross reference flags (XREF), defined in the Adopted Levels table are given for each adopted level. When a level in an individual reaction or decay data set may correspond to more than one adopted level, the flag for that data set is given in lower case. In case of ambiguity, the energy from a particular data set is given as a comment.

Adopted Levels, Gammas data set

The Adopted Levels and γ radiations tables in the NDS are generated from an Adopted Levels, Gammas data set in ENSDF. This data set represents the best values for the level and γ properties as determined by the evaluator on the basis of all the available information.

The following information is included in an Adopted Levels, Gammas data set.

For the nuclide:

1. **Q**(β^-): β^- decay energy [always presented as $Q(\beta^-)=M(A,Z)-M(A,Z+1)$] and α decay energy [Q(α)] for the ground state.
2. **S(n) and S(p)**: Neutron and proton separation energies.
3. **XREF**: Cross-reference symbol assignments for the various experimental data sets.

For each level:

1. **E(lev)**: Excitation energy (relative to the ground state).
2. **J$^\Pi$**: Spin and parity with arguments supporting the assignment.
3. **$T_{1/2}$ or Γ**: Half-life or total width in center of mass.
4. **Decay branching** for the ground state and isomers (an isomer is defined as a nuclear level with $T_{1/2}\geq0.1$ s or one for which a separate decay data set is given in ENSDF).
5. **Q**,μ: Static electric and magnetic moments.
6. **XREF Flags** to indicate in which reaction and/or decay data sets the level is seen.
7. **Configuration assignments** (*e.g.*, Nilsson orbitals in deformed nuclei, shell-model assignments in spherical nuclei).
8. **Band assignments** and possibly band parameters (*e.g.*, rotational bands in deformed regions).
9. Isomer and isotope shifts (usually only a literature reference is given).
10. Charge distribution of ground states (usually only a literature reference is given).
11. Deformation parameters.
12. **B(E2)↑,B(M1)↑**,..: Electric or magnetic excitation probabilities when the level half-life or the ground-state branching is not known.

For γ-ray and E0 transitions:

1. **Placement** in level scheme.
2. **Eγ**: Measured γ-ray or E0 transition energy.
3. **Iγ**: Relative photon intensity from each level.
4. **Mult**,δ: Electric or magnetic multipole character, the mixing ratio, and nuclear penetration parameter.
5. **CC**: Total internal-conversion coefficient (when $\geq1.0\text{x}10^{-4}$).
6. **B(EL)(W.u.),B(M1)(W.u.)**,..: Reduced transition probabilities in Weisskopf units.

Reaction and decay data sets

These data sets include information about different types of experiments and may include data sets for β decay, α decay, isomeric transition (IT) decay, Coulomb excitation, charged-particle reactions [such as, (d,p) and (t,p)], heavy-ion reactions [such as, (^{40}Ar,xnγ)], (γ,γ'), and mesonic atoms.

The following policies apply to the presentation of data in reaction and decay data sets. Any deviation from these policies will be noted by the evaluator.

1. The J$^\Pi$ values in decay data sets are taken from the associated Adopted Levels, Gammas data set. For reaction data sets the J$^\Pi$ values are from the reaction data. The J$^\Pi$ value to the capture state in thermal-neutron capture is assigned assuming s-wave capture.

GENERAL POLICIES - Presentation of Data (cont.)

2. The multipolarity of a γ ray and its mixing ratio given in a decay data set are from the associated Adopted γ radiation table.
3. The term "absolute intensity" has the same meaning as the term "emission probability", and the term "relative intensity" is equivalent to "relative emission probability" or "relative emission rate." The former are given as intensities per 100 decays.
4. Beta and electron-capture intensities are per 100 decays of the parent and are usually deduced from γ intensity imbalance for the levels fed. The separation of I(ε+β^+) into I(ε) and I(β^+) is based on theoretical ε/β^+ ratios. The log *ft* values for nonunique transitions are calculated as for allowed transitions.
5. Particle transition intensities (other than β's) are per 100 particle decays. The total particle branching is given both in the drawings and in the tables.
6. Tabular γ-ray intensities are relative values. The normalization factor to convert them to absolute intensities [photons per 100 decays of the parent for decay data sets, or photons per 100 neutron captures for (n,γ) data sets, *etc.*] is given in a footnote.
7. Radiations from the decay of neutron or proton resonances are not presented. The energies and other level properties for bound levels deduced from resonance experiments are included. Primary as well as secondary γ's following thermal-neutron capture are generally included.
8. BEλ, BMλ for the excitation of levels are generally given.
9. Up to three references that make major contributions to the information in a specific data set are given in the data set heading. These major references also appear in the drawings.

Organization of material

Within each A chain, information is presented by nuclides which are arranged in order of increasing Z. There is an index for each evaluation which is followed by an isobaric diagram. A table of properties for the ground state and isomeric levels for all nuclides of the A chain is given following or with the isobaric diagram.

For each nuclide, ^{A}Z, the arrangement of material and conventions for inclusion in tables are described below.

1. Adopted levels in ^{A}Z - All adopted level properties are shown for each level, together with explanatory comments.
2. Adopted γ radiations in ^{A}Z.
3. Band structure is shown where known.
4. Levels and radiations in ^{A}Z from radioactive decays - Decays are ordered by increasing A, Z, and excitation energy of the parent.
    a. Table of levels deduced from the decay.
    b. Tables of radiations observed in the decay.
    c. Decay Scheme
5. Levels and γ rays in ^{A}Z from nuclear reactions - Reactions are ordered by increasing A, Z of the target, then by increasing A, Z of the incident nucleus. A heading is given for each reaction.
    a. Table of levels deduced from the reaction.
    b. Table of γ rays observed in the reaction, if any.
    c. Level Scheme, if γ rays were observed and placed.

Theory

A reference "Theory 1967Xy01" indicates theoretical predictions computed by the authors of 1967Xy01. A reference "Theory" alone indicates a determination by the evaluator of theoretical predictions described below.

Internal Conversion Coefficients

Theoretical conversion electron coefficients are obtained by cubic spline interpolation (BrIcc, 2008Ki07) from tables calculated using the relativistic Dirac-Fock method and the so called ”Frozen Orbitals” approximation (2002Ba85,2002Ra45). These tables cover the K, L1, L2, ... R2 shells, E1–E5 and M1–M5 multipolarity, Z=10 to 110 atomic numbers and Eγ transition energies from 1 keV above shell binding energy up to 6000 keV. Conversion electron coefficients for transitions outside the Eγ, A, or Z ranges of BrIcc are obtained as follows: for Eγ < 6000 keV and Z=3 and interpolation from the tables of Band, *et al.* (1976Ba63); for Eγ > 6000 keV, by graphical interpolation from the tables of Trusov (1972Tr09). For Z>110 atomic numbers theoretical conversion electron coefficients are obtained by cubic spline interpolation from the tables of Band, *et al.* (2002Ba85) and Kibedi, *et al.* (2008Ki07).

Angular Distribution and Correlation Coefficients

The coefficients required for analysis of directional correlation, polarization correlation, directional distribution, and polarization distribution data are obtained as described by Steffen (1971St47,1971St48). In particular, we adopt the phase convention for the mixing ratio, δ, defined by Krane and Steffen (1970Kr03). Particle parameters required for the analysis of correlation and distribution data involving conversion electrons are obtained by graphical interpolation from tables of Hager and Seltzer (1968Ha54). The expression for the deorientation coefficient required to account for intermediate unobserved mixed radiations is given by Anicin (1972An20).*

A tabulation of gamma-gamma directional-correlation coefficients is given by Taylor, *et al.* (1971Ta32). These authors use the Steffen phase convention.

Penetration Parameters

Penetration parameters required for the analysis of internal conversion data and angular correlation or distribution data involving electrons are obtained by graphical interpolation from tables of Hager and Seltzer (1969Ha61).

Internal Pair Conversion Coefficients

Theoretical pair conversion coefficients for E1-E3 and M1–M3 multipolarities are obtained by cubic spline interpolation (2008Ki07) from tables of Schluter and Soff (1979Sc31) for Z=1–49 and from Hofmann and Soff (1996Ho21) for Z=50–100.

E0 Electronic Factors

For E0 transitions, electronic factors are obtained by cubic spline interpolation (2008Ki07) from tables of Hager and Seltzer (1969Ha61) for Z=30–38, L_1– and L_2–shell and transition energies starting 6 keV above K-shell binding energy up to 1500 keV; Bell et al., (1970Be87) for Z=40–102, K–, L_1– and L_2–shell and transition energies starting from 51.1 keV (Z=40–58), 102.2 keV (Z=60–82), 153.3 keV (Z=84–96), 204.4 keV (Z=98–102) up to 2555 keV; and Passoja and Salonen (1986PaZM) for K–shell, Z=8–38, transition energies of 511 keV to 12775 keV and for pair conversion, Z=8–40, transition energies of 1430.8 keV to 12775 keV.

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* As pointed out by these authors, most earlier references which discuss this coefficient define it incorrectly.

GENERAL POLICIES – “THEORY”

Beta Transitions (β^-, β^+, and ε decays)

Beta transitions are classified as allowed or forbidden:

(a) Allowed transitions occur between states with the same parity ($\pi_i \bullet \pi_f$=+1) and with a spin difference of J_i - J_f =ΔJ=0 or ±1.

> The spins of the emitted beta and neutrino can couple to S=0 (called Fermi transitions) or to S=1 (called Gamow-Teller transitions). Transitions with ΔJ=±1 are pure Gamow-Teller decays, and pure Fermi transitions can only occur between J=0 nuclear states. All other ΔJ=0 transitions are mixed Fermi and Gamow-Teller decays.

(b) Forbidden transitions are further subdivided into their order of forbiddenness, the transitions becoming slower as the order increases. A general definition for an n–times forbidden beta transition is

$\Delta\pi=\pi_i \bullet \pi_f =(-1)^n$,
ΔJ=n, n+1 (except first-forbidden which may have ΔJ=0)
ΔJ= n+1 transitions are called nth forbidden-unique beta transitions

Therefore:

- first-forbidden transitions (n=1) occur between states with different parity ($\pi_i \bullet \pi_f$ =-1) and with a spin difference of ΔJ= 0, ±1, ±2; those with ΔJ= ±2 are specified as being first-forbidden unique;
- second-forbidden (n=2) beta transitions occur between states with same parity ($\pi_i \bullet \pi_f$ =+1) and ΔJ=±2, ±3; the ΔJ= ±3 transitions being further specified as second-forbidden unique;
- for third-, fourth-forbidden, etc., transitions, n=3, 4, etc., respectively.

An allowed/forbidden beta transition may also be hindered or may be fast as a result of the nuclear structure of the initial and final states involved. See, for example, 1966Ko30 for a detailed discussion of the operators involved in various types of beta transitions. The selection rules for Nilsson states in deformed regions are tabulated in 1971El12. Violation of these selection rules could slow a beta transition. The beta transitions, therefore, may be hindered due to structures of the states involved. Definitions of some of the frequently used terms are given below:

- If a ΔJ=0 transition occurs between analog states (*i.e.* states having the same isospin and configuration), then the decay is very fast and is called “superallowed.”
- Special cases of “allowed unhindered” (au) transitions in deformed region are discussed in section 33 of Bases for Spin and Parity.
- “Isospin-forbidden” transitions refer to the decays between J=0 states of different isospin (*i.e.* non-analog states).
- “*l*-forbidden” transitions are those with Δ*l* > ΔJ, where Δ*l* is the change in *l* between the initial and final shell-model states.
- In deformed regions, if ΔK, the change in the K quantum number between the initial and final states, is larger than the spin change, ΔJ, the transition is called “K-forbidden.”

Log *ft* values, capture-to-positron ratios, and electron-capture ratios for allowed, first-forbidden unique, and second-forbidden unique transitions are obtained as described by Gove and Martin (1971Go40). This reference also contains a tabulation of log *ft* values and total capture-to-positron ratios for allowed and first-forbidden unique transitions.

A fast (strong) beta transition has a low *ft* value; forbidden transitions have larger *ft* values. Compilations of log *ft* values for known and well-established beta transitions appear, for example, in 1998Si17 and 1973Ra10.

The rules for various types of beta transitions are given in section 7-11 under Bases for Spin and Parity.

Atomic Processes

X-ray fluorescence yields are obtained from Bambynek, *et al.* (1972Bb16) for Z≤92 and from Ahmad (1979Ah01) for Z>92.

Electron binding energies for Z<84 are taken from Bearden and Burr (1967Be73) and from Porter and Freedman (1978Po08) for Z>84.

α-Decay Hindrance Factors

The α-hindrance factors (the ratio of the measured partial half-life for α-emission to the theoretical half-life) are obtained from the spin-independent equations of Preston (1947Pr17). The nuclear radius for each even-even nucleus is determined by defining, for the g.s. to g.s. α-transition, the hindrance factor (HF)≡1. For odd-A and odd-odd nuclei, the radius parameters are chosen to be the average of the radii for the adjacent even-even nuclei (1998Ak04). In cases where only one adjacent even-even radius is known, the extrapolated/interpolated value for the unknown radius is used in the calculation. A survey of the dependence of α-hindrance factors on asymptotic quantum numbers and the variation of α-hindrance factors within rotational bands is given for A≥229 in 1972El21.

Electromagnetic Transition Rates

The Weisskopf single-particle estimates for the half-lives of electric and magnetic multipole radiation of energy E_γ are (1952Bl97)

$$T_{1/2W}(EL)=0.190\left(\frac{L}{L+1}\right)\left(\frac{3+L}{3}\right)^2\frac{[(2L+1)!!]^2}{A^{2L/3}}\left(\frac{164.44}{E\gamma\ (MeV)}\right)^{2L+1}x10^{-21}\ s$$

$$T_{1/2W}(ML)=3.255\ A^{2/3}\ T_{1/2W}(EL)$$

for a nuclear radius of 1.2 $A^{1/3}x10^{-13}$ cm.

Unweighted and Weighted Averages

If $x_1 \pm \Delta x_1$, $x_2 \pm \Delta x_2$, $...x_n \pm \Delta x_n$ are n independent measurements of a given quantity, Δx_i being the uncertainty in x_i, then the weighted average of these measurements is $\overline{x} \pm \Delta\overline{x}$, where

$$\overline{x} = W\Sigma x_i/(\Delta x_i)^2,$$
$$W = 1/\Sigma\ (\Delta x_i)^{-2},$$

and $\Delta\overline{x}$ is the larger of

$$(W)^{1/2}$$
$$\text{and } [W\Sigma(\Delta x_i)^{-2}(x-x_i)^2/(n-1)]^{1/2}.$$

The unweighted average of these same measurements is given by $\overline{x} \pm \Delta\overline{x}$, where

$$\overline{x} = \Sigma x_i/n,$$
$$\Delta\overline{x} = [\Sigma\ (\overline{x} - x_i)^2/n(n-1)]^{1/2.}$$

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS

PROPOSITIONS ON WHICH STRONG ARGUMENTS ARE BASED

Ground States

1. The ground state of an even-even nucleus has $J_\pi = 0^+$.
2. Spin determinations by such techniques as atomic-beam resonance, paramagnetic resonance, electron-spin resonance, and optical spectroscopy give correct values.

Gamma Transitions

3. The agreement of the measured value of a single conversion coefficient with the theoretical value for a multipolarity which is well separated from the value for any other multipolarity determines the transition multipolarity.
4. In all other cases if there is no other evidence for multipolarity, agreement of two or more measured conversion coefficients or ratios with theoretical values is necessary in order to establish the multipolarities of a transition and its mixing ratio.
5. Since an E0 transition can proceed only by conversion or pair production, pure E0 is ruled out if photons are observed.
6. Recommended upper limits for γ-ray strengths (Γ_γ/Γ_w,Γ_w-Weisskopf estimate) for various A values are given below.

	Γ_γ/Γ_W (Upper Limit)		
Character*	A=6–44[a§]	A=45–150[b,c]	A>150[d]
E1 (IV)	0.3[#]	0.01	0.01
E2 (IS)[e]	100	300	1000
E3	100	100	100
E4	100	100[†]	
M1 (IV)	10	3	2
M2 (IV)	3	1	1
M3 (IV)	10	10	10
M4		30	10

* 'IV' and 'IS' stand for isovector and isoscalar

† Γ_γ/Γ_w(Upper Limit)=30 for A=90–150

\# Γ_γ/Γ_w(Upper Limit)=0.1 for A=21–44

§ Γ_γ/Γ_w(Upper Limit)=0.003 for E1 (IS),
10 for E2 (IV), 0.03 for M1 (IS), 0.1 for M2 (IS)

[a] From 1979En05

[b] From 1979En04

[c] From 1981En06

[d] Deduced from **ENSDF** by M. J. Martin

[e] In super-deformed bands the E2 transitions can have $\Gamma_\gamma/\Gamma_w>1000$.

Beta Transitions§

7. If log *ft* < 5.9, the transition is allowed: ΔJ=0 or 1, Δπ=no (no change in parity). Superallowed (ΔT=0) $0^+\rightarrow0^+$ transitions have log *ft* in the range 3.48 to 3.50. Isospin forbidden (ΔT=1) $0^+\rightarrow0^+$ transitions have log *ft*>6.4. If 3.6<log *ft*<6.4, the transition is not $0^+\rightarrow0^+$.
8. If log $f^{1u}t$<8.5 (log $f't$ < 7.4), ΔJ=0,1; Δπ=yes or no, *(log $f^{1u}t$=log $f't$+1.079)*.
9. If log *ft*<11.0, ΔJ=0,1; Δπ=yes or no or ΔJ=2, Δπ=yes.
10. If log *ft*<12.8, ΔJ=0,1,2; Δπ=yes or no.
11. If log $f^{1u}t\geq8.5$ (log $f't \geq 7.4$) and if the Fermi plot has the curvature corresponding to a shape factor (p^2+q^2), then the transition is first-forbidden unique (ΔJ=2, Δπ=yes).

γγ Directional Correlation

$$W(\theta) = \sum_{k\text{-even}} A_k P_k (\cos\theta)$$

12. If a gamma-gamma directional-correlation experiment yields $A_2\approx+0.36$ and $A_4\approx+1.1$, then the spin sequence is $0 \rightarrow 2 \rightarrow 0$.
13. Results of γγ(θ) are strong evidence for excluding spin sequences for which the theoretical A_2 or A_4 falls well outside the experimental range.

βγ Directional Correlation

$$W(\theta) = \sum_{k\text{-even}} A_k(\beta)A_k(\gamma)P_k(\cos\theta)$$

14. If $|A_2(\beta)|\geq0.1(A_4=0)$, the transition is not allowed. The converse is not true.
15. If $A_4(\beta)\neq0$, the transition is neither allowed nor first forbidden.
16. If $A_4(\beta)=0$, the transition is allowed or first forbidden.

βγ Polarization Correlation

$$P(\theta) = \frac{\sum_{k-\text{odd}} A_k(\beta)A_k(\gamma)P_k(\cos\theta)}{W(\theta)}$$

17. In allowed transitions,

β^- $A_1(\beta)<0$ if $J_i=J_f$
β^+ $A_1(\beta)>0$ if $J_i=J_f$

β^- $A_1(\beta)\geq0$ if $J_i=J_f+1$
$A_1(\beta)<0$ if $J_i=J_f-1$

β^+ $A_1(\beta)\leq0$ if $J_i=J_f+1$
$A_1(\beta)>0$ if $J_i=J_f-1$

18. If $A_4(\beta)\neq0$, the β-transition is not allowed. The converse is not always true.

γ Angular Distribution

19. In the angular distribution of gamma rays from deexcitation of states populated in high-spin reactions (for a typical value of σ/J=0.3, where σ is the magnetic substate population parameter):

a. If $A_2\approx+0.3$ and $A_4\approx-0.1$, the transition is generally ΔJ=2 (stretched quadrupole). (The same A_2 and A_4 values are possible for ΔJ=0, D+Q transitions also, but such transitions are less common. A_4=0 for ΔJ=0, dipole transition).
b. If $A_2\approx-0.2$ and $A_4\approx0$, the transition is generally ΔJ=1 (stretched dipole).
c. If $A_4>0$ ($A_2\approx+0.5$ to -0.8), the transition is ΔJ=1, D+Q.

γ DCO Ratio

In the angular correlation (DCO) of gamma rays from deexcitation of states populated in high-spin reactions (for a typical value of σ/J=0.3, where σ is the magnetic substate population parameter):

20. For ΔJ=2, stretched quadrupole as a gating transition:

a. R(DCO)≈1.0, the transition is generally ΔJ=2 (stretched quadrupole). (The same value is possible for ΔJ=0, dipole but such transitions are less common).
b. If R(DCO)≈0.5, the transition is generally ΔJ=1 (stretched dipole).
c. If R(DCO) differs significantly from ≈0.5 or ≈1.0, the transition is ΔJ=1 (or 0), D+Q.

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§ Note that for nuclei at, or very near to, closed shells, log *ft* values may be smaller. For example, in the mass region around Z=82, the upper limit of 5.9 given in #7 could be 5.1.

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS - continued

PROPOSITIONS ON WHICH STRONG ARGUMENTS continued

γ DCO Ratio continued

21. For $\Delta J=1$, stretched dipole as a gating transition:
   a. If $R(DCO)\approx 2.0$, the transition is generally $\Delta J=2$ (stretched quadrupole). (The same value is possible for $\Delta J=0$, dipole transitions, but such transitions are less common).
   b. If $R(DCO)\approx 1.0$, the transition is generally $\Delta J=1$ (stretched dipole).
   c. If $R(DCO)$ differs significantly from ≈ 2.0 or ≈ 1.0, the transition is $\Delta J=1$ (or 0), D+Q.

Reactions

22. Low-energy Coulomb excitation is predominantly E2 excitation.

23. Coulomb excitation determines J^{π} if the excitation probability agrees with the calculated values of Alder (1960Al23).

24. The spin of the compound nuclear state resulting from thermal-neutron capture is equal to the spin of the target nucleus plus or minus 1/2.

25. Primary γ's from neutron capture are E1, M1, E2, or M1+E2.

26. If the angular distribution in a single-nucleon transfer reaction can be fitted with a unique L value, the spin of the final state J_f is related to the spin of the initial state J_i by

$$\vec{J}_f = \vec{J}_i + \vec{L} + \vec{1/2}$$

with parity change if L is odd.

27. If the vector analyzing power for a single-nucleon transfer reaction shows a clear preference between $J=L+1/2$ and $J=L-1/2$ and if the L value is known, then the J value is determined.

28. Generally for the states populated in high-spin reactions, spins increase with increasing excitation energy. This is a result of the fact that these reactions tend to populate yrast or near yrast states.

29. If the angular distribution can be fitted with a unique L-value the J^{π} of the final state is related to the J^{π} of the initial state by

$\vec{J}_f = \vec{J}_i + \vec{L}$, $\pi_f\pi_i=(-1)^L$, for the following cases

   a. A strong group observed in (p,t), (t,p), and (^{3}He,n) reactions (strong groups are assumed to result from two identical nucleons transferred in a relative s state)
   b. A strong group observed in the α-particle transfer reaction (^{6}Li,d).
   c. (e,e') and (α,α') inelastic scattering.

30. In reactions with $J^{\pi}=0^+$ target, projectile, and ejectile, if the yield of a group at 0° or 180° is
   a. non-zero, the parity of the final state is $(-1)^{J_f}$
   b. zero at several uncorrelated energies, the parity of the final state is $(-1)^{J_f+1}$

31. In reactions with a polarized $J^{\pi}=1$ projectile in the m=0 substate, with $J^{\pi}=0^+$ ejectile and target, if the yield of a group at 0° or 180° is
   a. non-zero, the parity of the final state is $(-1)^{J_f+1}$
   b. zero at several uncorrelated energies, the parity of the final state is $(-1)^{J_f}$

Regions of Strong Nuclear Deformation

The systematic occurrence of rotational-band structure in the strongly deformed nuclides can be a considerable help in making $J\pi$ assignments, since one can also use the level energy as one of the considerations. This frequently makes it possible to assign a $J\pi$ value to a level with confidence from data which, absent such structure, might yield an ambiguous assignment.

32. Level-energy considerations. If the couplings among the states are not too strong, the energies of the lower members of a band can be expressed by the relatively simple relation (see, *e.g.*, 1971Bu16 and references therein):

$$E(J,K)=AX+BX^2+CX^3+\ldots$$
$$+(-1)^{J+K}\prod_{i=1-K}^{K}(J+i)\ \{A_{2K}\}+B_{2K}X+\ldots\} \qquad (1)$$

where $X=J(J+1)-K^2$

The **inertial parameter**, A, exhibits a systematic behavior in the various regions of strongly deformed nuclei, which can be helpful in assigning levels to rotational bands. In some instances (*e.g.*, strong Coriolis coupling) where the A values depart significantly from systematic trends, this observation can itself be useful, since it can help establish the presence of such effects and, hence, provide evidence for the relevant nucleonic configurations.

For the case of K=1/2 bands, the **decoupling parameter**, a, which is characteristic for each such band, is given by the ratio A_1/A in (1). Establishing a value for the decoupling parameter of a proposed band can be useful in assigning a nucleonic configuration to it - and *vice-versa.*

33. Allowed-unhindered beta transitions. In this region, beta transitions having log *ft* values <5.0 are classified as "allowed unhindered" (*au*). Such transitions take place between one-quasiparticle orbitals having the same asymptotic quantum numbers. In the "rare-earth" region ($90 \leq N \leq 112$, $60 <\approx Z <\approx 76$), four such orbital pairs are known: [532], near the beginning of this region; [523], near the middle of this region; [514], above the middle of this region; and, at the high end, [505]. Observation of an *au* transition is definitive evidence for the presence of the particular pair of orbitals.

34. Coulomb excitation. If a sequence of levels having "rotational-like" energy spacings is found to be excited with enhanced probabilities, this is evidence that this sequence (at least below the first "backbend") forms the ground-state rotational band for the nuclide involved. If the E2 transition probabilities involved are large (tens of Weisskopf units or larger) and comparable to each other, then this is definitive evidence for both a band structure and the sequence of $J\pi$ values, assuming one of the spins is known.

35. Alpha decay. Observation of a "favored" α transition (HF<4) indicates that the two states involved have the same nucleonic configuration. If a sequence of levels having "rotational-like" energy spacings is associated with the level fed by this favored transition and these levels have HF's that vary according to the established trend within rotational bands (1972El21), then this sequence can be considered to form a rotational band whose nucleonic configuration is the same as that of the alpha-decaying state. If the $J\pi$ value of this latter state and its configuration are known, then the corresponding quantities can be considered to be known for the band in the daughter nuclide or *vice versa.*

36. Single-nucleon-transfer reactions (light-ion-induced). For a single-nucleon transfer reaction induced by light ions (^{4}He and lighter), the characteristic pattern of cross sections among rotational-band members ("fingerprint") can be used to assign a set of levels as specific $J\pi$ members of a band based on a particular Nilsson configuration, if the fingerprint agrees well with that predicted by the Nilsson-model wavefunctions and is distinct from those expected for other configurations in the mass region. (This method is even stronger if angular distributions giving unique L values, or vector analyzing powers, support the assignments for one or more of the levels.)

SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS - continued

PROPOSITIONS ON WHICH STRONG ARGUMENTS ARE BASED continued

High-spin states

In the decay of high-spin states, commonly produced in heavy-ion induced compound nuclear reactions or in highly excited nuclides created as products of nuclear fission or in Coulomb excitation, the multipolarities of the deexciting γ transitions and the relative spins and parities of the levels are generally determined from angular distributions, angular correlations (DCO ratios), linear polarizations and internal-conversion coefficients. In addition, relative energy-level spacings and the increase of γ intensity with decreasing excitation energy are important clues.

37. For a deformed nucleus, a regular sequence of gamma-ray transitions can be assigned to a $\Delta J=2$ (decoupled) or a $\Delta J=1$ (strongly-coupled or magnetic-dipole) rotational-band structure with definite spin-parity assignments if:
  a) the spin and parity of at least one level in this band is unambiguously determined; and
  b) for $\Delta J=2$ band structures, at least one of the in-band transitions has a well established E2 multipolarity, or, for $\Delta J=1$ band structures,
    i) at least one of the crossover ($\Delta J=2$) transitions has a well established E2 multipolarity, or,
    ii) at least one of the stopover ($\Delta J=1$) transitions has a well established M1 (or M1+E2) multipolarity or (for parity-doublet bands) E1 multipolarity; and
  c) some other in-band transitions are stretched quadrupole for the $\Delta J=2$ band structures or stretched dipole (or dipole plus quadrapole) for $\Delta J=1$ band structures.

Alpha Decay

38. The hindrance factor for an α transition from the ground state of an even-even nucleus to the ground state of the daughter nucleus is 1.0 by definition. For odd-A and odd-odd nuclei, hindrance factors ≤ 4 identify favored α transitions, and these connect states having the same spin, parity and configuration.

39. For α-decay between two states, one of which has J=0, the parity change is given by $\Delta\pi=(-1)^{\Delta J}$.

Proton Decay

40. The spin and parity of a level exhibiting proton radioactivity and belonging to a nearly-spherical odd-Z, even-N nucleus can be taken equal to a particular set of Jπ values of the emitted proton if a) the transition reaches the ground state of the daughter nucleus, b) the proton Jπ values are physically reasonable, i.e., supported by systematic studies / Shell Model calculations, c) the calculated proton radioactivity half-life for those Jπ values is smaller than the experimental value, and d) the calculated proton radioactivity half-lives for the other physically possible Jπ values are far larger or far smaller than the experimental value.

PROPOSITIONS ON WHICH WEAK ARGUMENTS ARE BASED

1. In cases where gammas of one multipolarity "cluster" in one time region in the half-life vs. energy plot, as is true for M4's, other γ's whose half-lives fall in this cluster may be assigned the corresponding multipolarity.

2. In cases where a cluster of two multipolarities, *e.g.* M1 and E2 occupies one time region, a new gamma of which the half-life falls in this region may be assigned one of the two multipolarities or a mixture of the two.

3. Whenever $\Delta J\geq 2$, an appreciable part of the gamma transition proceeds by the lowest possible multipole order.

4. The spin and parity of a parent state may be inferred from the measured properties of its assumed isobaric analog resonance, and vice versa.

5. Low-lying states of odd-A nuclei have shell-model spins and parities, except in the regions where deformations appear. This argument is much stronger when supported by expected cross-section strengths (C^2S) in single-nucleon transfer reactions.

It is recognized that some shell-model predictions are stronger than others. For example, the shell model would mildly deny that the ground-state J^{π} of the 39th proton be $3/2^{-}$, but emphatically deny its being $3/2^{+}$. However, we have not included this distinction here and consider all shell-model arguments to be weak.

6a. For low-lying states of odd-odd spherical nuclei, the Nordheim rules (1950No10):

$J = j_p + j_n$, if $j_p=l_p + -1/2$ and $j_n = l_n + -1/2$;
$J = |j_p-j_n|$, if $j_p = l_p + - 1/2$ and $j_n=l_n -+ 1/2$.

may be helpful in obtaining the ground-state spins and parities, if there is supporting evidence.

6b. For excited states of strongly deformed odd-odd nuclei, the Gallagher-Moszkowski rules (1958Ga27) may be helpful in deducing the relative positions of the two two-quasiparticle states formed by the two different couplings of the quasiparticle constituents, if there is supporting evidence. Here, the state corresponding to the parallel alignment ($\Sigma=1$) of the projections (=1/2) of the intrinsic spins of the two odd particles is expected to lie lower than that produced by the antiparallel ($\Sigma=0$) alignment. This can be particularly useful in establishing the ground state Jπ values and nucleonic configurations for odd-odd nuclei.

(In the strongly deformed even-even nuclei, the opposite is expected to obtain, i.e., the $\Sigma=0$ coupling should lie lower than that with $\Sigma=1$. In these nuclei, however, the experimental situation is less clear since the two-quasiparticle excitations occur at or above the pairing gap, where the level densities are high and couplings to vibrational excitations can affect the two two-quasiparticle states differently.)

7. Statements similar to 5 and 6 based on other models.

8. Statements based on interpolation or extrapolation of regional trends, such as shown in 1971Bu16, 1972El21, 1977Ch27, 1990Ja11 and 1998Ja07 for the rare-earth and heavy-mass regions.

9. All statements connected with the nonobservation of expected transitions.

10. Rules extracted in the survey by 1972El21 for unfavored α transitions can be used to deduce the configuration of the parent or the daughter level, if the configuration of the other is known.

11. For magnetic moments, the extreme rarity of pure single-particle states and observation of large deviations from free-nucleon g-factors in nuclei means that comparison between the experiment and the 'Schmidt Limit' estimates (based on such pure states) is not a sound basis for spin or parity assignment. The magnetic moments or g-factors, however, can give supporting, and in some cases decisive, evidence for assignments where predictions for possible alternatives, using g-factors based on local systematics of measured moments, differ widely.

For excited states, the 'collective' aspects of the state frequently make substantial contribution to the magnetic moment. The correct g-factor for this contribution, however, is a matter of detailed theory and any potential assignment based on assumed g(collective)=Z/A must be viewed with caution.

12. In the absence of angular distribution/correlation data or other supporting arguments, a regular sequence of gamma-ray transitions in high-spin data may be assigned to a common structure or band with tentative spin-parity assignments if either the bandhead or some other low-lying member of this structure has reasonably well established spin and parity.

This statement is based on the scarcity of counter-examples and the observation that few E2 γ's are as slow as M3's, few E2's as slow as E3's, *etc.*

CONVENTIONS USED IN NUCLEAR DATA SHEETS

Units

Energies	keV
Cross Sections	barns
Magnetic dipole moments	nuclear magnetons (μ_N)
Electric quadrupole moments	barns
B(EL)	e^2b^L
B(ML)	$\mu_N^2\, b^{L-1}$

Uncertainties ("Errors") The uncertainty in any number is given one space after the number itself:

4.623 *3*	means 4.623 ±0.003
4.6 h *12*	means 4.6 ±1.2 h
$5.4\text{x}10^3$ *2*	means 5400 ±200
4.2 *+8–10*	means $4.2^{+0.8}_{-1.0}$
–4.2 *+8–10*	means –(4.2 *+10–8*)=$-4.2^{+0.8}_{-1.0}$

? Question Mark given after a quantity often indicates doubt as to the existence or the value of the quantity. For example, a "?" given after the $T_{1/2}$ value indicates that the assignment of that half-life to the associated level is not certain.

( ) Parentheses have the following interpretation for different quantities in the tabular data:

Quantity	Meaning of parentheses
Jπ	Jπ based upon weak arguments. See SUMMARY OF BASES FOR SPIN AND PARITY ASSIGNMENTS.
L transfer or Mult.	Possible value but not definitely established experimentally.
Other	Value deduced (*i.e.*, is not directly measured) or taken from other sources.

Examples:

$J^\pi=(1/2,3/2)^-$
Weak arguments limit the spin to 1/2 or 3/2. Strong arguments indicate negative parity.

$J^\pi=4^{(+)}$
Strong arguments show the spin is 4; weak arguments suggest positive parity.

L=(3)
L value tentatively established as 3.

Mult.=(M1)
Radiation character tentatively established as M1.

Mult.=M1(+E2)
Radiation character includes E2 with a mixing ratio, $|\delta|$, that may be >0.

[ ] Brackets

$7/2^-$[514] Nilsson asymptotic quantum numbers, K^π [N n_z Λ]

Assumed quantity, *e.g.*, [M1+E2]

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