The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1939-21

Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data: Theory and Evaluation

28 April - 9 May, 2008

ENSDF - Reaction Data

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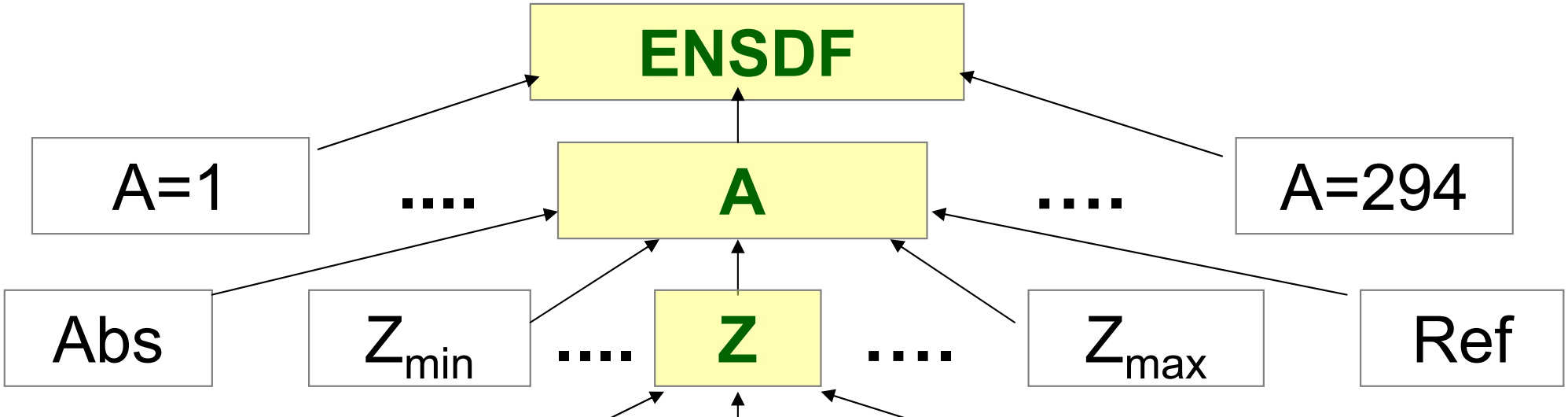
Workshop on *Nuclear Structure and Decay Data: Theory and Evaluation*
ICTP, Trieste, 28 April – 9 May 2008

ENSDF Database Structure



Adopted
(best values)
Q values
Levels:
(E, Jπ, T1/2, μ, Q, config, excitn.)
Gammas:
(E, Br, Mult, δ)

1 dataset

Decays
β^-
$\varepsilon+\beta^+$
α
β^-n
etc.

0 to ~6 datasets

Reactions
(HI,xnγ)
(p,p' γ)
(n, γ)
Coul. Exc.
(α,α')
(d,p)
etc.

0 to ~40 datasets

Summary

Principal Categories of Reactions.

- *Reactions in which gammas are not detected:*
  - Stripping and Pickup Reactions
  - Multi-particle Transfer Reactions
  - Charge-Exchange Reactions
  - Inelastic Scattering
  - Coulomb Excitation (particles detected)
  - Resonance Reactions …
- *Reactions in which gammas are detected:*
  - Summary of information available from γ-ray measurements
  - Inelastic Scattering
  - Nuclear Resonance Fluorescence
  - (light ion,xnypγ)
  - (heavy ion,xnypγ)
  - Particle Capture
  - Coulomb Excitation (γ's detected)

Gammas not detected

Measured Quantities of Interest:

- E(level) from particle energy spectrum or excitation function.
- L – angular momentum transfer
- S, C^2S - spectroscopic factors
- β_2, β_4 - deformation parameters (if model independent)
- Γ, Γ_i – total or partial widths for level
- B(Eλ), B(M λ) – transition probabilities
- Jπ, T – spin, parity, isospin

Stripping and Pickup

Examples:

Stripping: (d,p), (α,^{3}He), (pol d,p), (^{3}He,d), *etc*.

Pickup: (p,d), (^{3}He,α), (t,α), *etc.*

Quantities to Record:

• **E(level),** deduced by authors from charged particle spectrum.

• **L** and **S** or **C^{2}S** from authors' DWBA analysis:

$(d\sigma/d\omega(\theta))_{exp} = (d\sigma/d\omega(\theta))_{DWBA} \times N \times C^2S'$

where S'=S (pickup) or

S'=S x $(2J_f+1)/(2J_i+1)$ (stripping)

(**dσ/dω** for one angle should be given in suitably relabeled S field when spectroscopic-factor information is not provided by authors.)

• **J** from L±1/2 for polarised beam if vector analysing power shows clear preference between L+1/2 and L-1/2.

Relevant Documentation:

Target Jπ (unless 0^+)

Spectrum resolution (FWHM, keV)

Normalisation factor for DWBA analysis

Range of angles measured, lab or c.m. (but specify which).

Stripping and Pickup, ctd.

Deformed Nuclides; α and lighter beams:

$(d\sigma/d\omega(\theta))_{exp} / [(d\sigma/d\omega(\theta))_{DWBA} \times 2N] = c^2(jl)\, V^2$,

where c is amplitude of Nilsson state wavefunction for transferred nucleon, V is fullness factor describing partial filling of target nucleus orbitals.

• The pattern of cross sections among rotational-band members may provide a characteristic **fingerprint** for a specific Nilsson configuration, enabling a set of levels to be assigned as specific J members of a band with that configuration if:

(i) the experimental fingerprint agrees well with that predicted by Nilsson-model wave functions, and

(ii) the fingerprint differs distinctly from those for other plausible configurations.

Example: $(d\sigma/d\omega(60°))$ calculated (1997Bu03) for $^{226}Ra(t,\alpha)^{225}Fr$:

Orbital:	1/2[400]	1/2[530]	**1/2[541]**	3/2[402]	3/2[651]	**3/2[532]**	Expt.	Mixed
J=3/2	23	14	1.5	103	0.0	0.7	~1.5	0.9
J=5/2	7.6	0.2	13	4.6	0.03	6.2	14	10
J=7/2	0.4	39	2.0	1.2	0.0	3.3	20	4.1
J=9/2	0.05	0.4	33	0.05	2.0	26	~45	49

Reality (not so simple!): 3/2[532] Coriolis mixed with 1/2[541] fits σ, energy.

Multi-particle Transfer

Examples:

(p,t), (α,d), (t,p), (α,p), (^{6}Li,d) …

Quantities to Record:

- E(level)
- L – if angular distribution can be fitted by a unique value

Deduced Quantities:

Jπ- from J(target)+L (vector sum) and $\pi_i\pi_f=(-1)^{Jf}$, for <u>strong</u> groups only in two-neutron, two-proton or α–particle transfer.

(*i.e.,* pairs of identical particles can be assumed to be transferred in relative s state for **strong** groups).

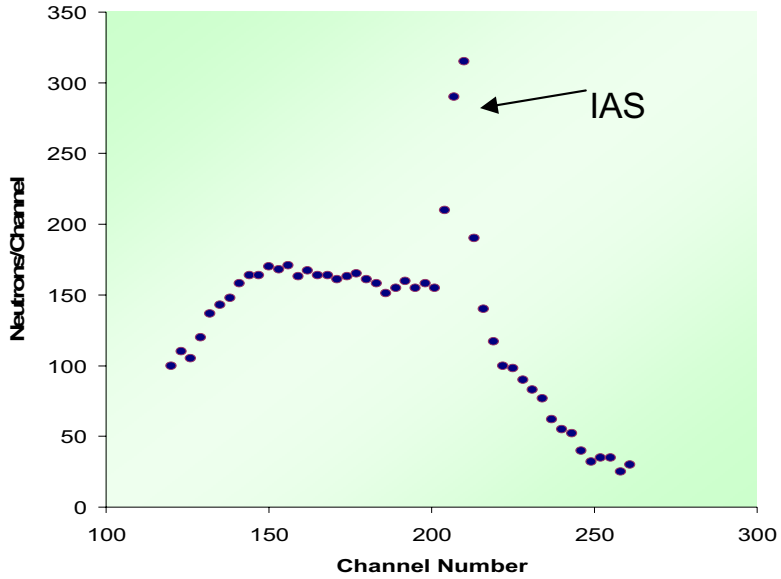
Charge-Exchange Reactions

Examples:

(p,n), (^{3}He,t)

Quantities of interest:

- E(level)
- Isobaric analog state information.



Inelastic Scattering

Examples:

(e,e'), (p,p'), (d,d'), (α,α') (at projectile energies **above** the Coulomb barrier).

Quantities to Record:

- E(level)
- L – if angular distribution is fitted by unique L value
- β2, β4 … - deformation parameters (if model independent); specify whether 'charge' or 'nuclear', if relevant (typically from (α,α') or (e,e')).
- B(Eλ), B(M λ) – transition probabilities (typically from (e,e')).

Coulomb Excitation
(particles detected)

Examples:
(p,p'), (d,d'), (α,α') with projectile energy **below** Coulomb barrier.

Quantities to Record:

- E(level)
- Jπ:
  - determined if the excitation probability agrees with that calculated by Alder (1960Al23).
  - low energy Coulomb excitation is predominantly E2
- B(Eλ) – for excitation (*i.e.,* B(Eλ)$\uparrow$)

Resonance Reactions

Examples:

(p,p), (p,X), (γ,n) … (excitation function data, σ(E), dσ/dω(θ,E))

Quantities of interest:

• E(level) – calculate from SP+E(p)(c.m.) or give as 'SP+976.3', *etc*., where 976.3 is E(p)(lab) for resonance; don't use both notations within the same dataset.

• Ep at resonance - can be given in relabeled 'S' or 'L' field.

• Partial widths – can be given in comments or relabeled 'S' field.

• Is this an isobaric analog state? (If so, specify state of which it is the analog).

• Is this a giant resonance? (If so, which one?)

• Any Jπ information that can be deduced.

Note:

ENSDF is primarily concerned with bound levels, but includes all isobaric analog states, giant resonances, and unbound levels which overlap or give information on bound levels.

Reactions with Gammas Detected

Measured Quantities of Interest:

- E_γ - photon energy
- $I\gamma$ - relative intensity (or photon branching)
- α, α_K, … - electron conversion coefficients, usually from I(ce)/$I\gamma$; sometimes from intensity balance (note: this gives α_{exp}).
- K/L, L1/ L3 … - ce subshell ratios
- A_2, A_4 … - Legendre polynomial coefficients characterizing angular distribution ($\gamma(\theta)$) or angular correlation ($\gamma\gamma(\theta)$).
- DCO ratio – directional correlation of gammas from oriented nuclei.
- Asymmetry ratio - *e.g.*, $I\gamma(\theta_1)/I\gamma(\theta_2)$
- Linear polarization
- Level $T_{1/2}$ – from γ(t), DSAM, RDM, centroid-shift, delayed coincidence, *etc*., if measured in that reaction (state method used).
- g-factor – include if measured in that reaction

Reactions with Gammas Detected – ctd.

Deduced Quantities of Interest:

• E(level) – from least-squares adjustment of Eγ (GTOL), avoiding Eγ for lines that have uncertain or multiple placements whenever possible. Note serious misfits.

• Band structure – indicate via band flags for levels. (Note: life will be easier if a given band has the same band-flag character in each dataset in the nuclide!).

• Band configurations – justify when possible; band parameters may be informative, especially for K=1/2 bands.

• Jπ - it may be desirable to indicate authors' values in the reaction dataset and add parentheses in *Adopted Levels* if insufficient (or no!) supporting arguments are available (but note major discrepancies).

•Transition quadrupole moment (if authors give it; include on level comment record or in band description).

• M - transition multipolarity

• δ – mixing ratio (√((L+1)-pole/(L-pole)), Krane-Steffen sign convention.

Gamma-ray Energies

• Give measured energy and uncertainty (*i.e.*, do not correct for recoil energy loss).

• State source of data (unless obvious, *e.g.*, if only one keynumber)

• Uncertainties: if authors give uncertainty as:

(i) “0.3 keV for strong lines, 1 keV for weak or poorly resolved lines”; assign 0.3 to those which could be reasonably considered ‘strong’ and 1 to all others, but give authors’ statement in general comment on $E\gamma$ and define the $I\gamma$ that you consider ‘strong’ (or assign 1 keV to all).

(ii) “do not exceed 0.5 keV”; 0.5 could be assigned for all lines.

(iii) If no uncertainty is stated, point that out in a general comment [for the purpose of deducing E(level) using GTOL, a default of 1 keV (adjustable by user via control record at head of dataset) will be used and this should be noted in a comment on level energy]

• If measured $E\gamma$ not available but G record is needed in order to give other information, deduce it from level energy difference and remove recoil energy loss; give no $\Delta E\gamma$ and say where $E\gamma$ came from.

Gamma-ray Intensities

- Give relative intensities, if available (don't renormalise so strongest is 100).
- Don't mix data from different reactions, or data from same reaction at different energies, when entering RI on G records (use different datasets instead, or include in comments or tabulation).
- If branching ratios are measured independently (*e.g.*, from $\gamma\gamma$ coincidences), quote these also (*e.g.*, in a comment); one set of data may be more precise than the other.
- Give uncertainties whenever authors state them; if authors give both statistical and systematic uncertainties, show statistical on G record but state systematic in comment (so uncertainty in Iγ ratios is not distorted).
- If both prompt and delayed Iγ are given, use separate datasets for them or give one set under comments.
- For multiply-placed lines, specify whether quoted Iγ has been suitably divided between placements (& (undivided) or @ (divided) in column 77).

Conversion Coefficients

• Give measured α_K, α_L, *etc*., and subshell ratios (in comments or on continuation of G record); state how photon and ce intensity scales were normalised.

• Quote experimental coefficients (usually α) obtained using intensity balance arguments (these are frequently buried in the text of a paper); specify as “from intensity balance at xxxx level”, where relevant.

• Include α(theory) on G record (from BrIcc) when needed for calculation or argument (or α(theory)+α(pair) if Eγ > 1022 keV).

γ Linear Polarisation

γ linear polarisation data may be available from Compton polarimeter measurements of relative Iγ in planes perpendicular and parallel to reaction plane.
Such data may distinguish between <u>electric</u> and <u>magnetic</u> radiations.

Angular Distributions

I_γ as a function of angle θ with respect to beam direction:

$$\mathbf{W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)+\ldots}$$

- Include A_2, A_4 … ; these data are very important to evaluators and readers alike, as they provide information vital to transition multipolarity assignments.
- Remember that these are signed quantities.
- A_2, A_4 … depend on ΔJ, mixing ratio and degree of alignment σ/J, where σ is half-width of Gaussian describing the magnetic substate population.
- σ/J is usually determined from measurements of $W(\theta)$ for known $\Delta J=2$ transitions. However, many authors assume $\sigma/J=0.3$, for practical purposes.
- σ/J affects only the magnitudes of A_2, A_4.
- For high-spin states, $W(\theta)$ is largely independent of J.
- Alignment is reduced if level lifetime is not small.
- **$W(\theta)$ can determine ΔJ but <u>not</u> $\Delta\pi$.**

Angular Distributions – ctd.

Typical values of A_2, A_4 for θ relative to beam direction if $\sigma/J=0.3$
(from B. Singh, McMaster University)

ΔJ	Multipolarity	Sign of A_2	Sign of A_4	Typical A_2	Typical A_4
2	Q	+	-	+0.3	-0.1
1	D	-		-0.2	0.0
1	Q	-	+	-0.1	+0.2
1	D+Q	+ or -	+	+0.5 to -0.8	0.0 to +0.2
0	D	+		+0.35	0.0
0	Q	-	-	-0.25	-0.25
0	D+Q	+ or -	-	+0.35 to -0.25	0.0 to -0.25

DCO Ratios

Directional **C**orrelations of γ-rays from **O**riented states of Nuclei

• If γ_K (known multipolarity) and γ_U (unknown multipolarity) are measured in coincidence using detectors at angles θ_1 and θ_2 to the beam:

$$DCO = I(\gamma_U(\text{at } \theta_1) \text{ gated by } \gamma_K(\text{at } \theta_2)) / I(\gamma_U(\text{at } \theta_2) \text{ gated by } \gamma_K(\text{at } \theta_1)) .$$

• Sensitive to ΔJ, multipolarity and mixing ratio; **independent of $\Delta\pi$.**

• Gating transitions are frequently stretched Q, but stretched D may also be used, so specify which was used.

• Authors frequently indicate expected DCO values for stretched Q and stretched D transitions for the geometry used. It is helpful to state these.

• Remember that identical values are expected for stretched Q and for D, $\Delta J=0$ transitions (although the latter are less common).

DCO Ratios – ctd.

Typical DCO values for θ_1=37°, θ_2=79°, σ/J=0.3 (B. Singh, McMaster U.)

ΔJ_γ gate, Mult	ΔJ_γ	Mult	Typical DCO
2, Q	2	Q	1.0
2, Q	1	D	0.56
2, Q	1	D+Q	0.2 to 1.3
2, Q	0	D	1.0
2, Q	0	D+Q	0.6 to 1.0
1, D	2	Q	1/0.56
1, D	1	D	1.0
1, D	0	D	1/0.56

Multipolarity

• L and $\Delta\pi$ may be determined from measured subshell ratios or conversion coefficients.

• L alone can be determined by angular distributions or DCO ratios or γ asymmetry ratios.

• $\Delta\pi$ may be determined by γ linear polarisation measurements.

• When transition strengths are calculable ($T_{1/2}$ and branching known), **R**ecommended **U**pper **L**imits (RUL) can be used to rule out some multipolarities (*e.g.*, a stretched Q transition for which $B(M2)_W$ exceeds 1 can be assigned as E2). Similarly, for a D+Q transition with large mixing, RUL may enable the rejection of E1+M2.

• Assign Mult when measured information indicates a clear preference for that assignment; otherwise, let $\gamma(\theta)$ or DCO data speak for themselves. (Exception: if no measurement exists but mult. is needed for some reason, use the [M1+E2], *etc.*, type of entry.)

• Mult determined for a doublet will be not reliable; it can be given in comment (with disclaimer), but not on G record.

Mixing Ratios

- Include on G record whenever available.
- Calculate from conversion electron data or $\gamma\gamma(\theta)$ using the program DELTA, or from subshell ratios.
- Rely on authors' deductions from $\gamma(\theta)$, DCO or nuclear orientation data.
- Note: In (HI,xnγ) studies, model-dependent values of δ are sometimes deduced from in-band cascade to crossover transition intensity ratios; these could be given in comments (stating relevant K) if considered really important, but should not be entered on G record.
- Check that correct sign convention was used by authors. Convert to Krane-Steffen if not, and take special care if uncertainties are asymmetric (-2.3 +4-2 becomes +2.3 +2-4 upon sign reversal).

Inelastic Scattering

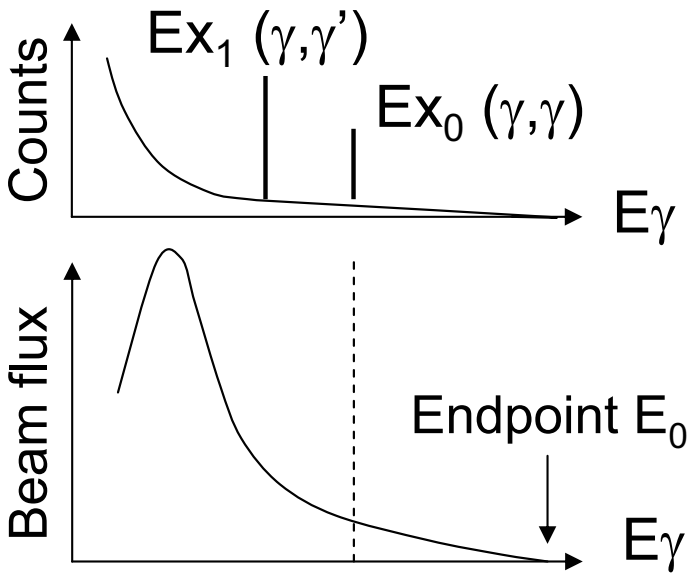
(p,p'γ), (n,n'γ), *etc*.; beam energies > Coulomb barrier.

Separate these datasets from those for (p,p'), (n,n') … and from that for Coulomb excitation.

Information of interest: typically Eγ, Iγ, $\gamma(\theta)$; maybe γ linear polarisation.

Nuclear Resonance Fluorescence

(γ,γ) and (γ,γ') measurements with Bremsstrahlung spectrum; low momentum transfer so excite low-spin states (mainly E1 and M1, but some E2 excitation).



- γ spectrum measured; areas of γ peaks at Ex_0 and Ex_1, combined with knowledge of $N\gamma(Ex_0)$, yields scattering cross sections from which width and branching information may be obtained.
- γ asymmetry differentiates D and Q excitation
- γ linear polarization differentiates M and E

Nuclear Resonance Fluorescence – ctd.

(Integrated) scattering cross section I_s (eV b) is often given:

$$I_s = ((2J+1)/(2J_0+1))\ (\Gamma\gamma_0\Gamma\gamma_f/\Gamma\gamma)\ (\pi\hbar c/E\gamma)^2\ W(\theta)/4\pi$$

where J is g.s. spin, J_0 is spin of excited level, $\Gamma\gamma \cong \Gamma$ is its total width and $\Gamma\gamma_0$, $\Gamma\gamma_f$ its decay widths for γ decay to the g.s. and the final state f (for elastic scattering, $\Gamma\gamma_0=\Gamma\gamma_f$); $W(\theta)$ represents the normalised angular distribution. Data are often taken at 127° where W=1 for D transitions.

- Give $\Gamma\gamma_0^2/\Gamma$ values (extract if necessary) on L record (col. 65 (value), 75 (uncertainty)); relabel field.
- If $\Gamma\gamma_f/\Gamma\gamma_0$ is measured, include relative branching on G records.

Γ is calculable from:

$$(\Gamma\gamma_0^2/\Gamma) / (\Gamma\gamma_0/\Gamma)^2$$

using known branching, or under the assumption $\Gamma=\Gamma\gamma_0+\Gamma\gamma_f$ (which needs to be stated).

- Then: $T_{1/2}$ (ps)= 0.456 /Γ (meV); include on L record.

Propagate uncertainties with care!

(Light Ion,xnypγ)

(p,xnγ), (^{3}He, xnγ), (α,pγ), *etc*.

- Separate from (HI,xnγ) studies, whenever practical.
- Separate from datasets in which gammas are not measured (*e.g*., do not combine (d,pγ) and (d,p)).

(Heavy Ion,xnypγ)

- Relative intensities will be different for different reactions and also for a given reaction measured at different beam energies; in general, it will be simplest to use separate datasets for each study that provides significant Iγ or branching data.
- (HI,xnγ) reactions tend to populate yrast (lowest energy for given J) levels or near-yrast levels; populated states tend to have spins that increase as the excitation energy increases.
- Use band flags to delineate deduced band structure. If authors give configuration for band, include this in band description.

(Heavy Ion,xnypγ) – ctd.

• Note inconsistencies in γ order, postulated Jπ, configuration, *etc*., compared with other studies and especially with that in *Adopted Levels, Gammas.*

• Beware of multipolarity and Jπ assignments for which no supporting measurements exist. Sometimes, unmeasured values inserted in order to generate a RADWARE band drawing live on in the published table of data; these do not qualify as 'measured data'!

• Multipolarities determined as D, Q, D+Q, *etc*, by γ(θ) or DCO are best left this way in the reaction dataset unless definite arguments exist (*e.g.,* from RUL) to establish Δπ; otherwise 'D' (strong Jπ argument) and '(D)' (weak Jπ argument) become indistinguishable when written as, say, (M1).

• Watch for and report statements of coincidence resolving time (or equivalent) since this might place a limit on level lifetime, thereby enabling RUL to be used to reject Δπ=yes for a transition multipolarity.

• For K=1/2 rotational bands, the decoupling parameter may give a clear indication of the Nilsson orbital involved in the band configuration.

(Heavy Ion,xnypγ) – ctd.

• For a deformed nucleus: if a cascade including ΔJ=2 and/or ΔJ=1 transitions is observed at high spin with regular energy progression, they can be assigned to a band with definite Jπ assignments if at least one level Jπ and one in-band transition with multipolarity E2 or M1(+E2) can be assigned independently.

• For near-spherical nuclei: if a cascade of ΔJ=1 transitions is observed at high spin with regular energy progression, those transitions may be assigned as (M1) transitions within a common band. Exception: in rare cases, nuclei can have alternating parity bands (reflection asymmetry); for these, ΔJ=1, Δπ=yes cascades occur.

• Note, however, that octupole-deformed nuclei may exhibit an apparent band structure which is really two ΔJ=2 rotational sequences of opposite parity, connected by cascading E1 transitions.

Special Case:

Superdeformed band data are updated continuously in ENSDF by Balraj Singh (McMaster University). One should check ENSDF as one finishes one's mass chain evaluation to be sure no SD-band data were added since the chain was downloaded for revision.

Capture Reactions

(p,γ), (n,γ) E=thermal, (n,γ) E=res, *etc*.

- Use separate datasets for thermal and resonance n-capture data.
- Primary and secondary transitions usually appear in the same dataset even if their intensities require different normalisations.
- The Jπ of the thermal neutron capture state(s) is Jπ(target)±1/2 (*i.e*., s-wave capture is assumed).
- In thermal neutron capture, the multipolarity of a primary γ is E1, M1, M1+E2 or E2.
- For resonance n capture, ENSDF does <u>not</u> include the resonances and their properties; it is adequate to just list the bound states fed, their interconnecting gammas and any conclusions concerning level Jπ.
- In average resonance n capture, inclusion of primary gammas and their reduced intensities (which carry information on final state Jπ) is optional; a list of final level E and deduced Jπ would suffice.

Coulomb Excitation

- If authors determine matrix element values, give them in comments and calculate B(Eλ) using

$$B(E\lambda) = |\langle M(E\lambda)\rangle|^2 / (2J_0+1)$$ where J_0 is g.s. spin.

- If authors give B(Eλ)↓, convert it to B(Eλ)↑ and include it with level information. $(B(E\lambda; i\rightarrow f)) = B(E\lambda: f\rightarrow i) \times (2J_f+1)/(2J_i+1))$
- In the strongly-deformed region, a cascade of E2 transitions with enhanced transition probabilities $(B(E2)_W > 10)$ provides definitive evidence for a rotational band and for the sequence of Jπ values, provided the Jπ of one level is known independently.
- Calculate level $T_{1/2}$ from B(Eλ) and adopted γ-ray properties when possible.
- Occasionally, mixing ratio or nuclear moment information can be extracted from matrix elements.
- Clearly indicate the direction for any B(Eλ) values given.