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Evaluation**

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**Reaction Data Sets**

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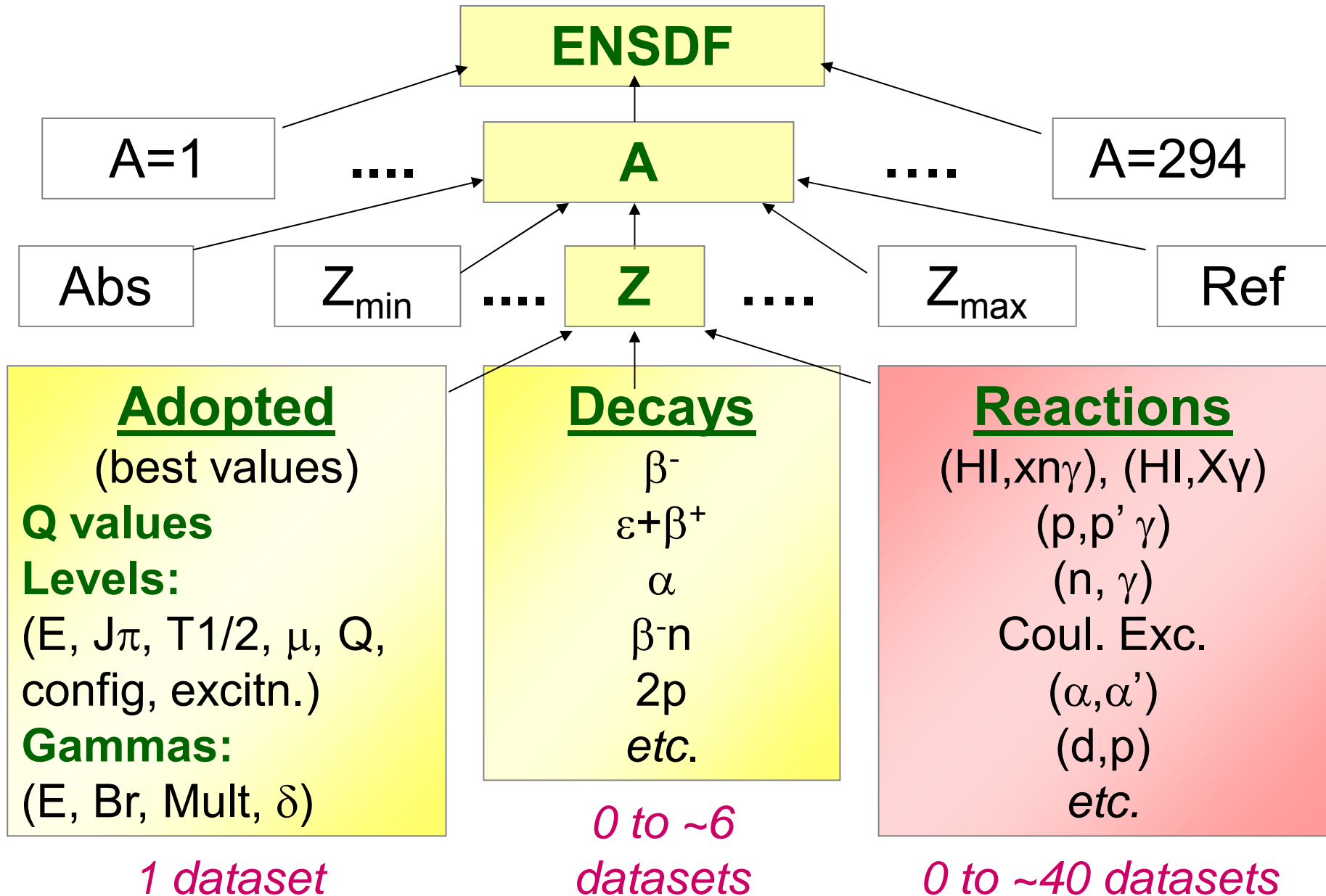


# ENSDF – Reaction Data

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# ENSDF Database Structure



# 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  $\gamma$ -ray measurements

- Inelastic Scattering

- Nuclear Resonance Fluorescence

- (light ion,  $xnyp\gamma$ )

- (heavy ion,  $xnyp\gamma$ )

- Particle Capture

- Coulomb Excitation ( $\gamma$ 's detected)

# Gammas not detected

## Measured Quantities of Interest:

- $E(\text{level})$  from particle energy spectrum or excitation function.
- $L$  – angular momentum transfer
- $S, C^2S$  - spectroscopic factors
- $\beta_2, \beta_4$  - deformation parameters (if model independent)
- $\Gamma, \Gamma_i$  – total or partial widths for level
- $B(E\lambda), B(M\lambda)$  – transition probabilities
- $J\pi, T$  – spin, parity, isospin

# Stripping and Pickup

## Examples:

Stripping: (d,p), ( $\alpha$ , $^3\text{He}$ ), (pol d,p), ( $^3\text{He}$ ,d), *etc.*

Pickup: (p,d), ( $^3\text{He}$ , $\alpha$ ), (t, $\alpha$ ), *etc.*

## Quantities to Record:

- **E(level)**, deduced by authors from charged particle spectrum.
- **L** and **S** or **C<sup>2</sup>S** from authors' DWBA analysis:

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

where  $S' = S$  (pickup) or

$$S' = S \times (2J_f + 1) / (2J_i + 1) \text{ (stripping)}$$

( $d\sigma/d\omega$  for one angle should be given in suitably relabeled S field when spectroscopic-factor information is not provided by authors.)

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

## Relevant Documentation:

Target  $J\pi$  (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; $\alpha$ and lighter beams:

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

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

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  $\sigma$ , energy.

# Multi-particle Transfer

## Examples:

(p,t), ( $\alpha$ ,d), (t,p), ( $\alpha$ ,p), ( ${}^6\text{Li}$ ,d) ...

## Quantities to Record:

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

## Deduced Quantities:

$J\pi$ - from  $J(\text{target})+L$  (vector sum) and  $\pi_i\pi_f=(-1)^{J_f}$ , for strong groups only in two-neutron, two-proton or  $\alpha$ -particle transfer.

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



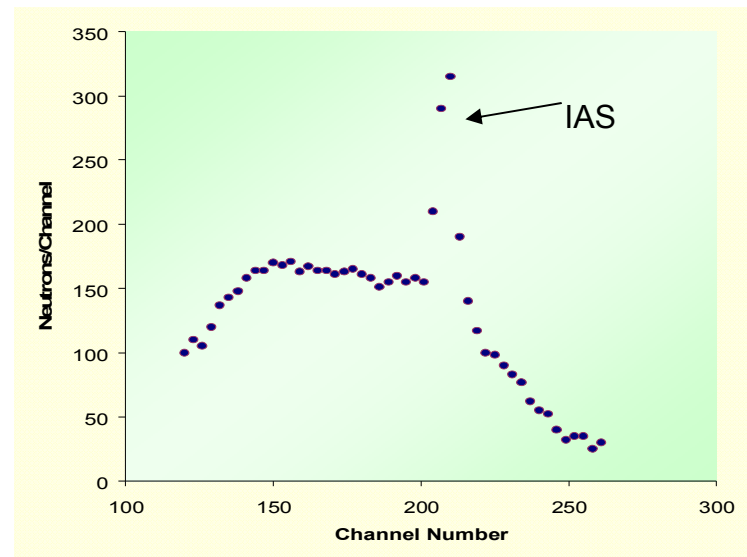
# Charge-Exchange Reactions

## Examples:

(p,n), ( $^3\text{He}$ ,t)

## Quantities of interest:

- E(level)
- Isobaric analog state information.



# Inelastic Scattering

## Examples:

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

## Quantities to Record:

- E(level)
- L – if angular distribution is fitted by unique L value
- $\beta_2, \beta_4 \dots$  - deformation parameters (if model independent); specify whether 'charge' or 'nuclear', if relevant (typically from ( $\alpha,\alpha'$ ) or (e,e')).
- $B(E\lambda), B(M\lambda)$  – transition probabilities (typically from (e,e')).

# Coulomb Excitation (particles detected)

## Examples:

(p,p'), (d,d'), ( $\alpha,\alpha'$ ) with projectile energy **below** Coulomb barrier.

## Quantities to Record:

- E(level)
- B(E $\lambda$ ) – for excitation (*i.e.*, B(E $\lambda$ ) $\uparrow$ )
- J $\pi$ :
  - determined if the excitation probability agrees with that calculated by Alder (1960AI23).
  - low energy Coulomb excitation is predominantly E2

# Resonance Reactions

## Examples:

(p,p), (p,X), ( $\gamma$ ,n) ... (excitation function data,  $\sigma(E)$ ,  $d\sigma/d\omega(\theta,E)$ )

## 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.
- $E_p$  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  $J\pi$  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. We now show **n resonance properties** also (e.g., from 2006MuZX or recent nTOFwork).

# Reactions with Gammas Detected

## Measured Quantities of Interest:

- $E_\gamma$  - photon energy
- $I_\gamma$  - relative intensity (or photon branching)
- $\alpha$ ,  $\alpha_K$ , ... - electron conversion coefficients, usually from  $I(\text{ce})/I_\gamma$ ; sometimes from intensity balance (note: this gives  $\alpha_{\text{exp}}$ ).
- 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  $\gamma(t)$ , 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  $E_\gamma$  (GTOL), avoiding  $E_\gamma$  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.
- $J\pi$  - 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
- $\delta$  – mixing ratio ( $\sqrt{((L+1)\text{-pole}/(L\text{-pole}))}$ ), Krane-Steffen sign convention.

# Gamma-ray Energies

- Give measured energy and uncertainty (*i.e.*, do not correct for recoil energy loss).
- Specify 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  $E(\text{level})$  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  $I_\gamma$  ratios is not distorted).
- If both prompt and delayed  $I_\gamma$  are given, use separate datasets for them or give one set under comments.
- For multiply-placed lines, specify whether quoted  $I_\gamma$  has been suitably divided between placements (& (undivided) or @ (divided) in column 77).



# Conversion Coefficients

- Give measured  $\alpha_K$ ,  $\alpha_L$ , *etc.*, and subshell ratios (in comments or on continuation of G record); state how photon and ce intensity scales were normalised.
- Quote any experimental coefficients (usually  $\alpha$ ) 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  $\alpha(\text{theory})$  on G record (from BrIcc) when needed for calculation or argument ( $\alpha(\text{theory}) + \alpha(\text{pair})$  if  $E_\gamma > 1022 \text{ keV}$ ).

## $\gamma$ Linear Polarisation

$\gamma$  linear polarisation data may be available from Compton polarimeter measurements of relative  $I_\gamma$  in planes perpendicular and parallel to reaction plane.

Such data may distinguish between electric and magnetic radiations.

# Angular Distributions

$I_\gamma$  as a function of angle  $\theta$  with respect to beam direction:

$$W(\theta) = 1 + A_2 P_2(\cos \theta) + A_4 P_4(\cos \theta) + \dots$$

- Include  $A_2, A_4 \dots$ ; 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.
- $A_2, A_4 \dots$  depend on  $\Delta J$ , mixing ratio and degree of alignment  $\sigma/J$ , where  $\sigma$  is half-width of Gaussian describing the magnetic substate population.
- $\sigma/J$  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.
- $\sigma/J$  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  $\Delta J$  but not  $\Delta\pi$ .**

# Angular Distributions - ctd.

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

$\Delta J$	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 Correlations of $\gamma$ -rays from Oriented states of Nuclei

- If  $\gamma_K$  (known multipolarity) and  $\gamma_U$  (unknown multipolarity) are measured in coincidence using detectors at angles  $\theta_1$  and  $\theta_2$  to the beam:

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

- Sensitive to  $\Delta J$ , multipolarity and mixing ratio; **independent of  $\Delta\pi$** .
- Gating transitions are frequently stretched Q, but stretched D may also be employed, 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  $\theta_1=37^\circ$ ,  $\theta_2=79^\circ$ ,  $\sigma/J=0.3$  (B. Singh, McMaster U.)

$\Delta J_\gamma$ gate, Mult	$\Delta J_\gamma$	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  $\gamma$  asymmetry ratios.
- $\Delta\pi$  may be determined by  $\gamma$  linear polarisation measurements.
- When transition strengths are calculable ( $T_{1/2}$  and branching known), **Recommended Upper Limits (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, $xn\gamma$ ) studies, model-dependent values of  $\delta$  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

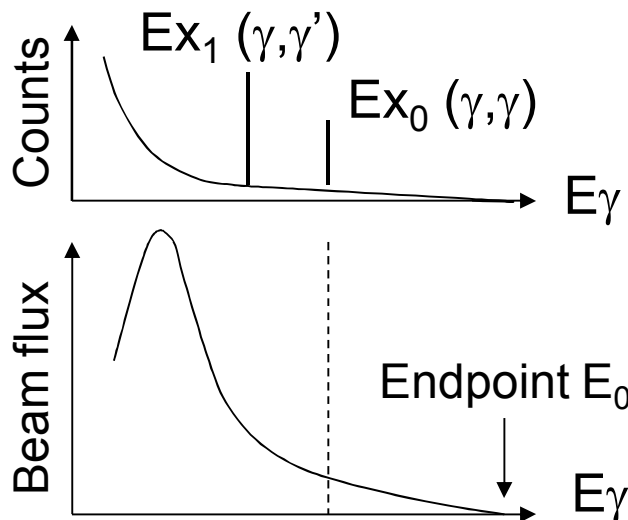
$(p,p'\gamma)$ ,  $(n,n'\gamma)$ , *etc.*; beam energies  $>$  Coulomb barrier.

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

Information of interest: typically  $E_\gamma$ ,  $I_\gamma$ ,  $\gamma(\theta)$ ; maybe  $\gamma$  linear polarisation.

# Nuclear Resonance Fluorescence

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



- $\gamma$  spectrum measured; areas of  $\gamma$  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.

- $\gamma$  asymmetry differentiates D and Q excitation
- $\gamma$  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  $J_0$  is g.s. spin,  $J$  is spin of excited level,  $\Gamma_{\gamma}\cong\Gamma$  is its total width and  $\Gamma_{\gamma_0}$ ,  $\Gamma_{\gamma_f}$  its decay widths for  $\gamma$  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  $127^\circ$  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.

$\Gamma$  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) =  $0.456 / \Gamma$  (meV); include on L record.

Propagate uncertainties with care!

## (Light Ion, $xn\gamma$ )

$(p, xn\gamma)$ ,  $({}^3\text{He}, xn\gamma)$ ,  $(\alpha, p\gamma)$ , *etc.*

- Separate from  $(\text{HI}, xn\gamma)$  studies, whenever practical.
- Separate from datasets in which gammas are not measured (*e.g.*, do not combine  $(d, p\gamma)$  and  $(d, p)$ ).

## (Heavy Ion, $xn\gamma$ )

- 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  $I_\gamma$  or branching data.
- $(\text{HI}, xn\gamma)$  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, $xn\pi\gamma$ ) - ctd.

- Note inconsistencies in  $\gamma$  order, postulated  $J\pi$ , configuration, *etc.*, compared with other studies and especially with that in *Adopted Levels, Gammas*.
- Beware of multipolarity and  $J\pi$  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  $\gamma(\theta)$  or DCO are best left this way in the reaction dataset unless definite arguments exist (*e.g.*, from RUL) to establish  $\Delta\pi$ ; otherwise 'D' (strong  $J\pi$  argument) and '(D)' (weak  $J\pi$  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  $\Delta\pi$ =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, xny $\gamma$ ) - ctd.

- For a deformed nucleus: if a cascade including  $\Delta J=2$  and/or  $\Delta J=1$  transitions is observed at high spin with regular energy progression, they can be assigned to a band with definite  $J\pi$  assignments if at least one level  $J\pi$  and one in-band transition multipolarity (E2 or M1(+E2)) can be assigned independently.
- For near-spherical nuclei: if a cascade of  $\Delta J=1$  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,  $\Delta J=1$ ,  $\Delta\pi=\text{yes}$  cascades occur.
- Note, however, that octupole-deformed nuclei may exhibit an apparent band structure which is really two  $\Delta J=2$  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

$(p,\gamma)$ ,  $(n,\gamma)$  E=thermal,  $(n,\gamma)$  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  $J\pi$  of the thermal neutron capture state(s) is  $J\pi(\text{target})\pm 1/2$  (*i.e.*, s-wave capture is assumed).
- In thermal neutron capture, the multipolarity of a primary  $\gamma$  is E1, M1, M1+E2 or E2.
- For resonance capture, ENSDF now includes the resonances and their properties, in addition to the bound states fed, the interconnecting gammas and any conclusions concerning level  $J\pi$ .
- In average resonance n capture, inclusion of primary gammas and their reduced intensities (which carry information on final state  $J\pi$ ) is recommended.

# Coulomb Excitation

- If authors determine matrix element values, give them in comments and calculate  $B(E\lambda)$  using

$$B(E\lambda; i \rightarrow f) = |\langle M(E\lambda) \rangle|^2 / (2J_i + 1) \text{ where } J_i \text{ is g.s. spin.}$$

- If authors give  $B(E\lambda)_\downarrow$ , convert it to  $B(E\lambda)_\uparrow$  for inclusion 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  $J\pi$  values, provided the  $J\pi$  of one level is known independently.
- Calculate level  $T_{1/2}$  from  $B(E\lambda)$  and adopted  $\gamma$ -ray properties when possible.
- Occasionally, mixing ratio or nuclear moment information can be extracted from matrix elements.
- Clearly indicate the direction for any  $B(E\lambda)$  values given.