ENSDF – Reaction Data

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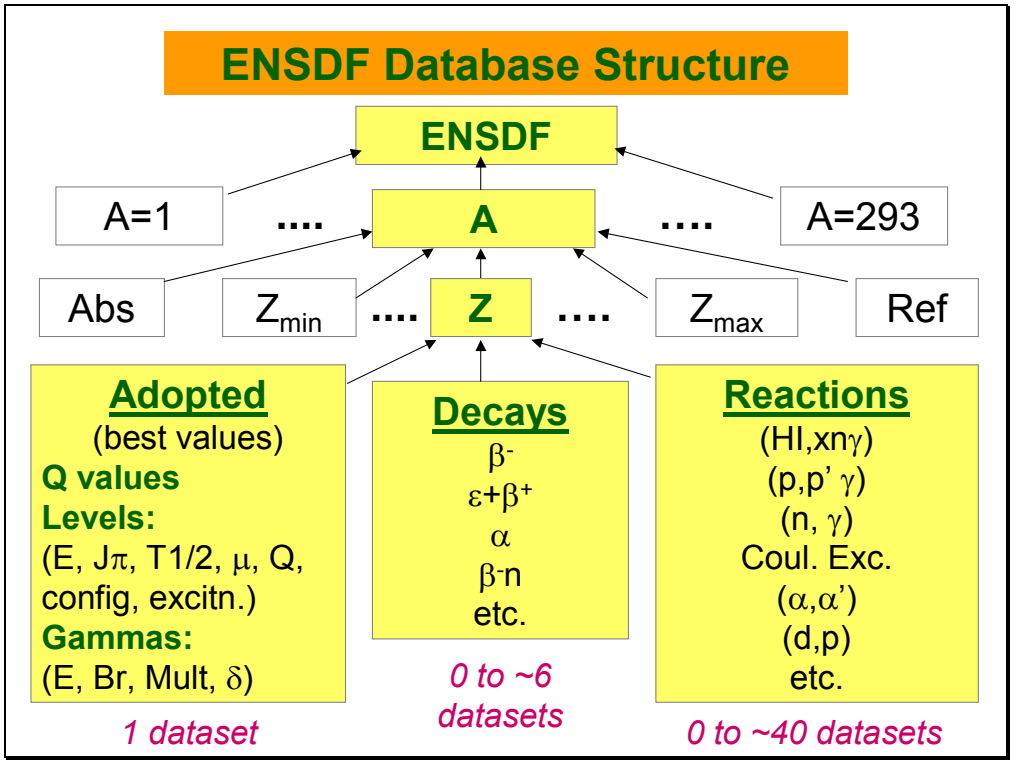


Summary

Principal Categories of Reactions:

- Reactions in which gamma emissions <u>are not</u> detected:
  - Stripping and Pickup Reactions
  - Multi-particle Transfer Reactions
  - Charge-Exchange Reactions
  - Inelastic Scattering
  - Coulomb Excitation (particles detected)
  - Resonance Reactions …
- Reactions in which gamma emissions <u>are</u> detected:
  - Summary of information available from γ-ray measurements
  - Inelastic Scattering
  - Nuclear Resonance Fluorescence
  - (light ion,xnypγ)
  - (heavy ion,xnypγ)
  - Particle Capture
  - Coulomb Excitation (γs detected)

Gamma emissions <u>not</u> detected

Measured Quantities of Interest:

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

Stripping and Pickup

Examples:

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

Pickup: (p, d), (^{3}He, α), etc.

Quantities to Record:

• **E(level)** from charged particle spectrum.

• **L** and **S** or **C²S** from DWBA analysis

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

where $S' = S$ (pickup) or

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

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

($d\sigma/d\omega$ is not normally given, but may be useful in absence of angular distribution; give in S field with suitable label.)

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 say which).

Stripping and Pickup

Deformed Nuclides; α and lighter beams:

•Pattern of cross sections among rotational-band members characteristic of a particular Nilsson configuration (**fingerprint)** enables a set of levels to be assigned as specific J members of that band if:

(i) fingerprint agrees well with that predicted by Nilsson-model wavefunctions, and

(ii) fingerprint is distinct from those for other possible configurations.

•Authors may give 'spectroscopic strength' (S) which can be entered in spectroscopic factor field (with suitable label).

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 strong groups only in two-neutron, two-proton or α–particle transfer

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

Resonance Reactions

Examples:

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

Quantities of interest:

E(level) – can be given as 'S(p)+976.3', etc., where 976.3 is E(p) for resonance (c.m. or lab. energy, but must specify which).

Is this an isobaric analog state? If so, specify state of which it is analog

Partial widths

Is this a giant resonance?

Note:

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

Reactions with Gamma Emissions - Detected

Measured Quantities of Interest:

- E_γ - photon energy
- Iγ - relative intensity (or photon branching)
- α, α_K, … - electron conversion coefficients, usually from I(ce)/Iγ, 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
- g-factor – include if measured in that reaction

Reactions with Gamma Emissions - Detected

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!)

• Jπ - default is adopted value; however, much more useful to indicate authors' values in reaction dataset and add parentheses in *Adopted Levels* if insufficient (or no!) supporting arguments are available

• 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 Eγ and define Iγ 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 out in general comment (for the purpose of deducing E(level) using GTOL, default of 1 keV (adjustable by user via control record at head of dataset)will be used and this should be noted in comment on level energy)

•If measured Eγ not available but G record needed in order to give other information, deduce from level energy difference and remove recoil energy loss; give no ΔEγ and state origin of Eγ

Gamma-ray Intensities

• Give relative intensities, if available (do not renormalise so strongest is 100).

• Do not 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), also quote these (e.g., in comments); 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 comments (so uncertainty in $I\gamma$ ratios is not distorted)

• If both prompt and delayed $I\gamma$ are given, use separate datasets or give one set under comments.

• For multiply-placed lines, specify whether quoted $I\gamma$ has been suitably divided between placements (& or @ 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 paper); specify as “from intensity balance at xxxx level” where relevant

• Include α(theory) on G record (from HSICC) when needed for calculation or argument

γ Linear Polarisation

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

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

- Inclusion of A_2, A_4 … is optional, but data are so useful to evaluators and readers alike, they really should be given whenever available!
- 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
- $W(\theta)$ is largely independent of J, for high-spin states
- Alignment is reduced if level lifetime is not small
- **$W(\theta)$ can determine ΔJ but <u>not</u> $\Delta\pi$**

Angular Distributions

Typical values of A_2, A_4 for θ relative to beam direction if $\sigma/J=0.3$
(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(γ_U(at θ_1) gated by (γ_K(at θ_2)/I(γ_U(at θ_2) gated by γ_K(at θ_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

•Authors frequently state expected DCO values for stretched Q and stretched D transitions for the geometry used; helpful to specify

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

DCO Ratios

Typical DCO values for $\theta_1 = 37°$, $\theta_2 = 79°$, $\sigma/J = 0.3$ (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., 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 Multpolarity only when measured information indicates clear preference for that assignment; otherwise, let $\gamma(\theta)$ or DCO data speak for themselves (exception: if no measurement exists but multpolarity is needed use [M1 + E2], etc., type of entry)

• Multpolarity determined for a doublet will be not reliable; can be given in comments (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 DELTA or from subshell ratios

• Rely on authors' deductions from $\gamma(\theta)$, DCO or nuclear orientation data

•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 – if not convert to Krane-Steffen, and take special care if uncertainties are asymmetric (-2.3 +4-2 becomes +2.3 +2-4 upon sign reversal)

Inelastic Scattering

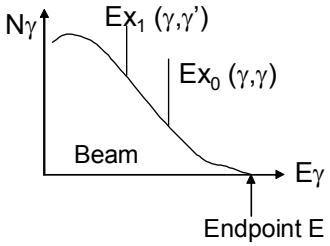
(p, p'γ), (n, n'γ), etc.; beam energies > Coulomb barrier

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, 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 section 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

(Integrated) scattering crossection I_s (eV b) is often given:

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

where J is g.s. spin, J_0 is spin of excited level, $\Gamma\gamma \cong \Gamma$ is total width and $\Gamma\gamma_0$, $\Gamma\gamma_f$ 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 (unc.)); 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 assumption $\Gamma = \Gamma\gamma_0+\Gamma\gamma_f$ (which needs to be stated).

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

Propagate uncertainties with care!

(Light Ion, xnypg)

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

Separate from (HI, xnγ) studies

Separate from datasets in which gammas are not measured (e.g., do not combine (d, pγ) and (d, p)).

(Heavy Ion,xnypγ)

• Relative intensities differ for different reactions and also for a given reaction measured at different beam energies; in general, 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 in band description

(Heavy Ion, xnypγ)

• 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; values inserted in order to generate a RADWARE band drawing sometimes live on in the published table of data; these do not qualify as '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 to establish $\Delta\pi$ (otherwise 'D' (strong Jπ argument) and '(D)' (weak Jπ argument) become indistinguishable when written as, say, (M1))

• Report statements of coincidence resolving time (or equivalent) since they 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, xnypγ)

• For near-spherical nuclei, if a cascade of ΔJ = 1 transitions is observed at high spin with regular energy progression, these 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

• For a well-deformed nucleus, if a cascade of ΔJ = 2 transitions is observed at high spin with regular energy progression, these transitions may be assigned as E2 transitions within a common band

• Octupole-deformed nuclei may exhibit an apparent band 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). Check ENSDF at the conclusion of a mass chain evaluation to be sure no SD-band data have been 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

• Jπ of the thermal neutron capture state(s) is Jπ(target)±$1/2^+$ (i.e., s-wave capture assumed)

• Thermal neutron capture: the multipolarity of a primary γ is E1, M1, E2 or M1+E2

• For resonance n capture, ENSDF does not include the resonances and their properties; list the bound states fed, their interconnecting gammas and any conclusions concerning level Jπ

• 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 give matrix element values, convert to 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 to B(Eλ)↑ and include with level information
- 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 independently known
- Calculate level $T_{1/2}$ from B(Eλ) and adopted γ-ray properties when possible