Nuclear Reactions

M. J. Martin
Nuclear Data Project
Oak Ridge National Laboratory
Oak Ridge TN 37830 U.S.A.
October, 2018

Techniques for measurements of lifetimes - 1

- The three most basic and widely applicable experimental techniques, and their approximate halflife ranges of effectiveness and accuracy are:

Halflife range (s)	Method
$T_{1/2} > 10^{-10}$	Electronic techniques
$5\times10^{-12} < T_{1/2} < 10^{-10}$	Recoil distance method (RDM)
$T_{1/2} < 5\times10^{-12}$	Doppler shift Attenuation method (DSAM)

with measurement accuracies of about 1, 10, and 15%, respectively

Techniques for measurements of lifetimes - 2

Recoil Distance Method (RDM)

In this method, nuclei are excited in a thin target and recoil freely in the forward direction with a mean velocity v. The excited nuclei travel through a plunger, and are stopped, or degraded by a movable metallic stopper/degrader.

Techniques for measurements of lifetimes - 3

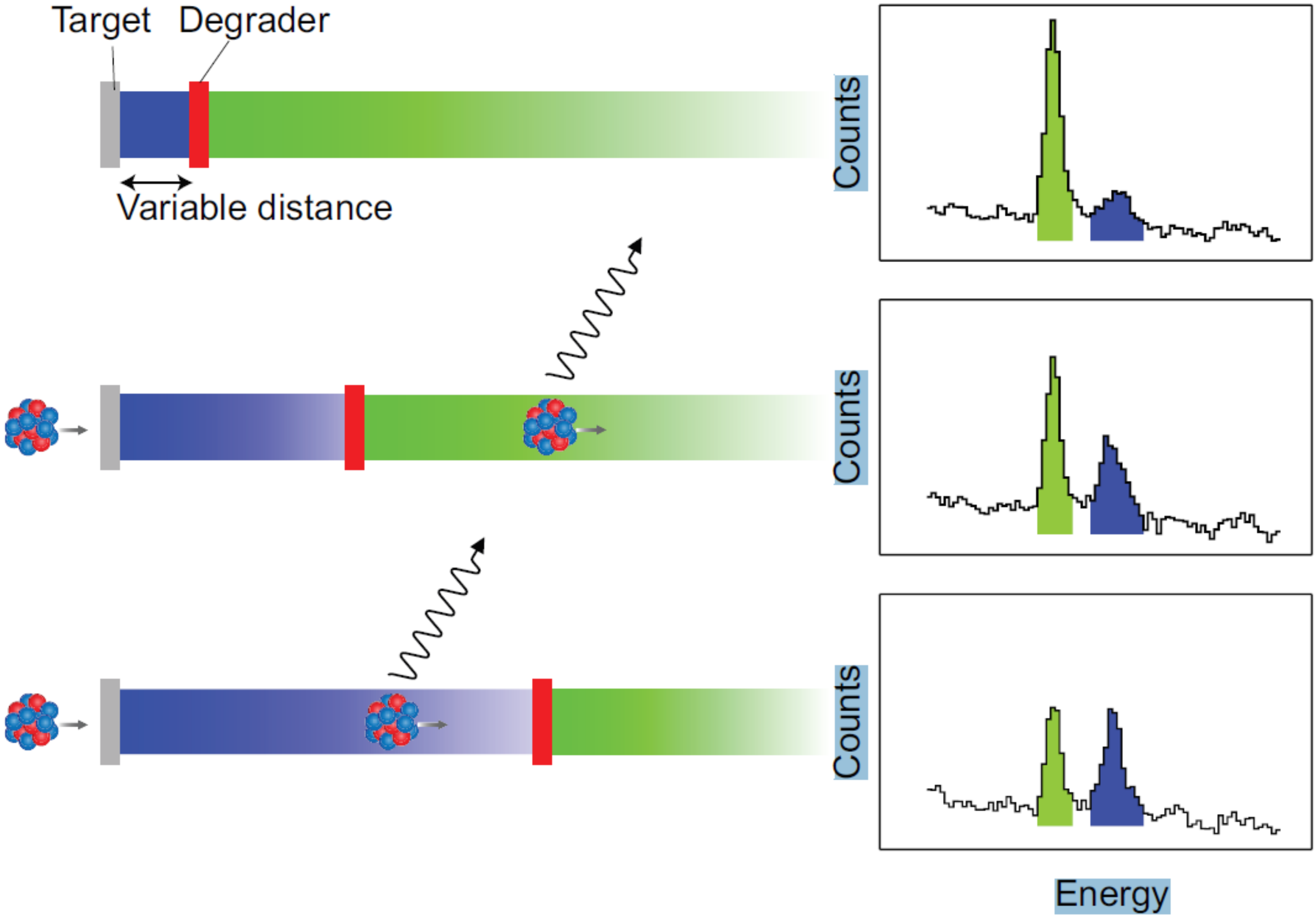
n the early applications of the recoil distance method, the plunger contained a topper that brought the beam of excited nuclei to rest. Deexcitation by this nsemble of recoiling nuclei are partitioned into two groups by the stopper.

. γ-rays emitted after the nuclei strike the stopper are at rest and have energies orresponding to the transition, $E_{\gamma 0}$.

. γ-rays emitted from nuclei still in flight have energies that are shifted to

$$E_{\gamma}=E_{\gamma 0}[(1-\beta_0^{2})^{½}]/[1-\beta_0\cos\theta]^{-1}$$

here β_0 (=v_0/c) is the initial recoil velocity of the residue formed in the center of ne target, and θ is the angle at which the γ's are detected relative to the recoil irection.



SU report MSUCL-1345

Techniques for measurements of lifetimes - 5

For small β_0, ≈ a few %, the expression for the Doppler shift is commonly substituted by its first order approximation

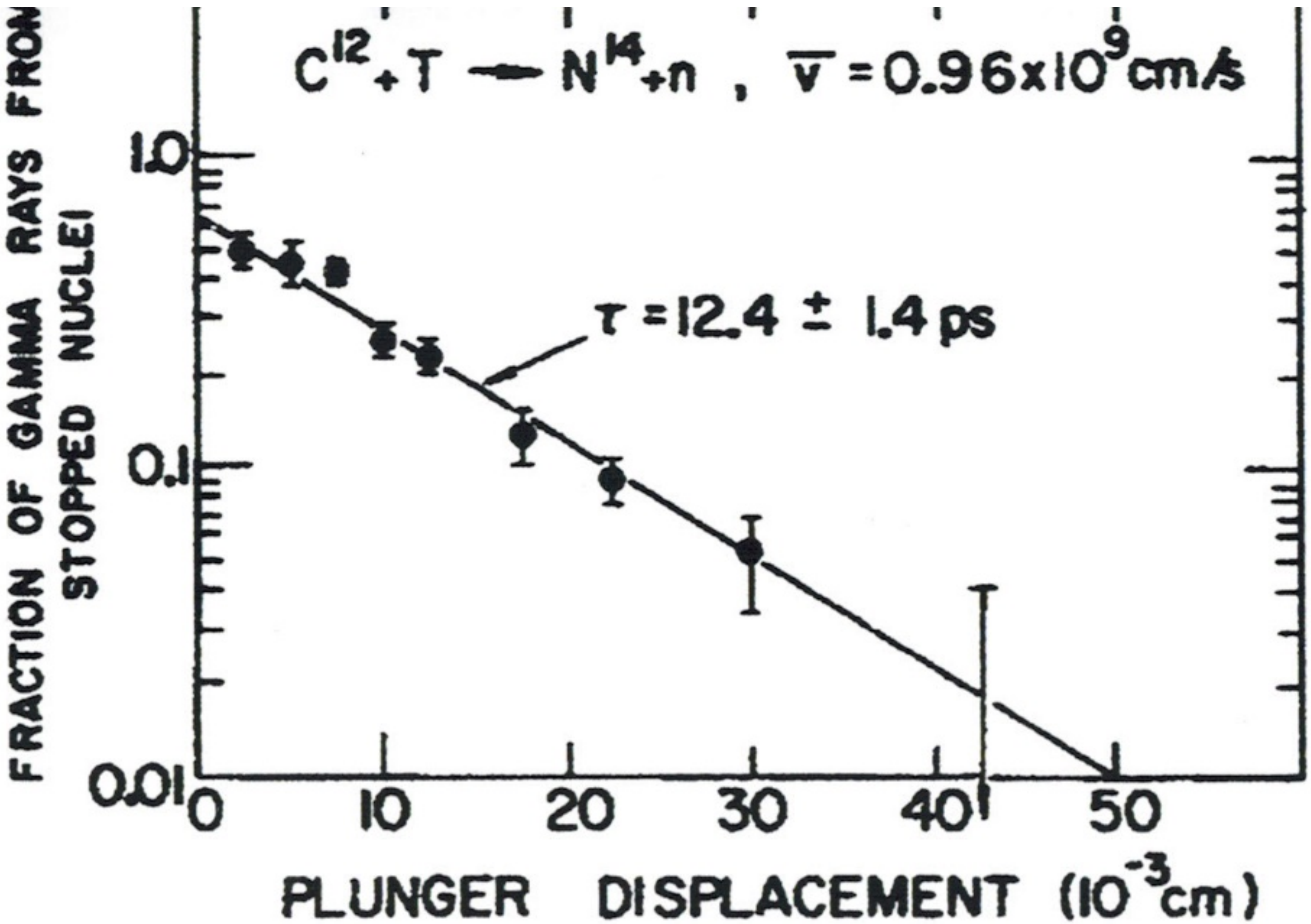
$$E_\gamma=E_{\gamma 0}(1+\beta_0\cos\theta)$$

For a target-stopper flight time of T, distance of D, and average velocity of v, one can define

$$R=I_u/(I_u+I_s)=e^{-T/\tau},\ \text{or}\ \ln R=-D/v\tau,$$

where I_u is the intensity of the unshifted peak, I_s is the intensity of the shifted peak, and τ is the mean life.

niques for measurements of lifetimes - 6



Techniques for measurements of lifetimes - 7

In more recent work, the stopper has been replaced by a degrader which slows the beam but allows it to pass through giving rise to two peaks with different Doppler shifts. With this construction, identification of the recoil fragments is possible with downstream particle detectors.

$$R = I(\text{after})/[I(\text{before}) + I(\text{after})]$$

and just with a stopper, the relative intensities of the peak areas as a function of the target-degrader separation determine the lifetime of the state of interest.

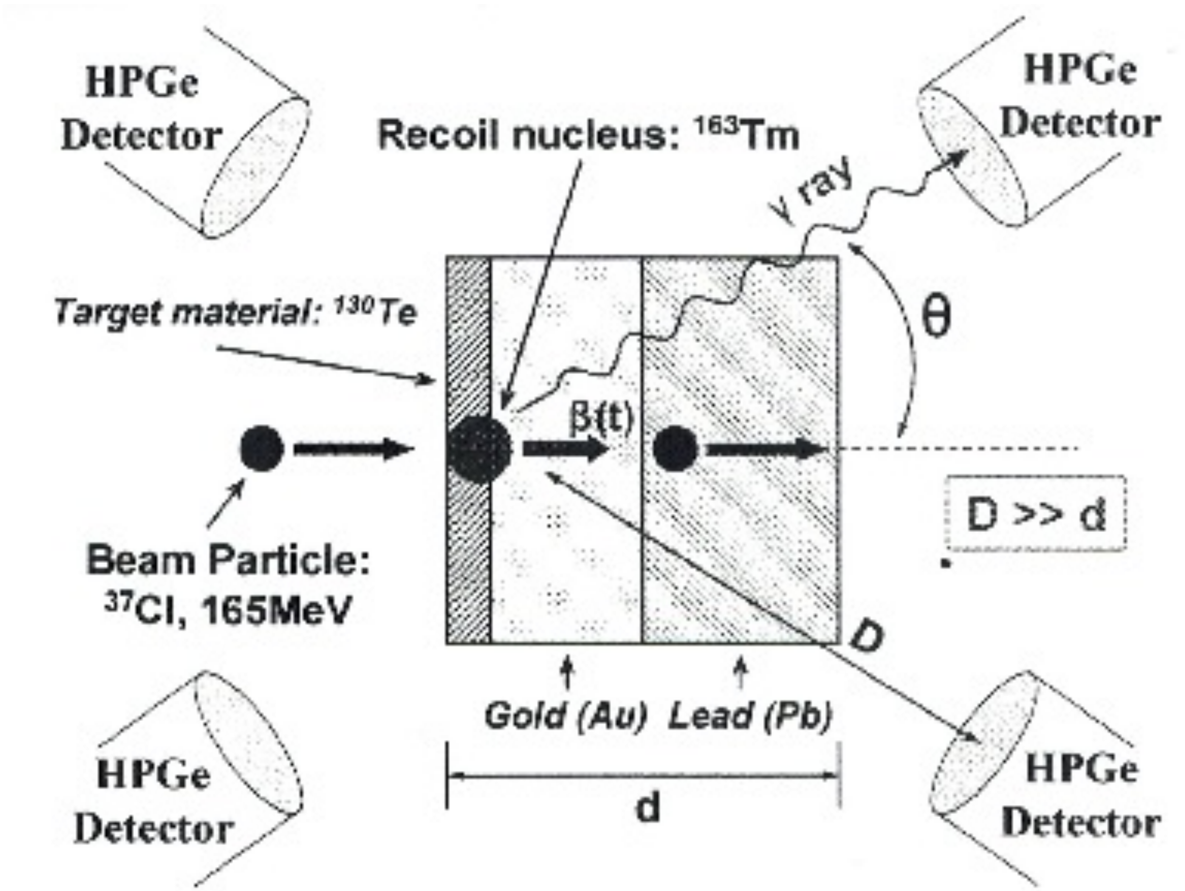
Techniques for measurements of lifetimes - 8

Doppler shift attenuation method (DSAM)

In this method, analysis of excited-state lifetimes normally employs production targets mounted on one or more layers of thick stopper foils (“backing”) which serve to slow down and stop the recoiling nuclei of interest in a well-defined manner.

Knowledge of the stopping power of the target is a limiting factor in the precision with which this method can measure lifetimes.

niques for measurements of lifetimes - 9



cm is the distance between target and detector. d ≈10^{-3} mm to 1 mm is the thickness of the target.

Techniques for measurements of lifetimes - 10

In the schematic, a ^{37}Cl beam reacts with a ^{130}Te target via a fusion-evaporation reaction. After four neutrons are evaporated from the compound system, the ^{163}Tm residue recoils with initial velocity $\beta_0=v_0/c$, slowing down in the ^{130}Te target layer and the Au backing until it is completely stopped. As it slows, Doppler-broadened γ's will be measured at an angle θ.

$$E_\gamma=E_{\gamma 0}(1+\beta_0\cos\theta) \qquad [1]$$

The stopping power of the target and backing material gives the velocity of the nucleus as a function of time by using the relation

$$dE/dx = -Mdv/dt$$

where M is the mass of the recoiling nucleus and dE/dx is the stopping power of the material that the nucleus is traveling through.

Techniques for measurements of lifetimes - 11

For fully Doppler-broadened transitions, the average energy can be determined experimentally from the shape of the peak, and used to extract the average velocity, β_{ave}, from Eq. [1].

The fraction of the full Doppler shift, F(τ), is defined as

$$F(\tau) = \beta_{ave}/\beta_0.$$

Many papers on lifetime measurements will give F(τ) as well as τ, but we do not quote this intermediate quantity in ENSDF.

Techniques for measurements of lifetimes - 12

- The major source of uncertainty in DSAM measurements is that due to the limited knowledge of stopping powers and in most cases this uncertainty is about 15%.

Coulomb excitation - 1

Coulomb excitation (x,x'γ) or (x,x') is an inelastic scattering reaction in which a charged particle transfers energy to a nucleus through the electromagnetic field, inducing transitions in the nucleus. A measurement of the E(γ) and I(γ) data, or of the scattered projectile in (x,x’), can be analyzed to yield information on transition matrix elements such as

$$B(EL:J_i \rightarrow J_f)=(2J_i+1)^{-1}<J_i||M(EL)||J_f>^2 \text{ and}$$

$$Q(J_f) \propto <J_f||M(E2)||J_f>$$

where Q is the static quadrupole moment. Similar relationships hold for magnetic multipoles.

Note that for the inverse transition induced by the same operator the detailed balance argument can be applied so that, for example,

$$B(E2:J_f \rightarrow J_i)=[(2J_i+1)/(2J_f+1)] \text{ x } B(E2:J_i \rightarrow J_f)$$

Coulomb excitation - 2

he transition probability for a γ ray of multipolarity L is related to the B(EL) and B(ML) alues. In terms of level halflives, in seconds, one has, for an E2 +M1 γ,

$$T½(J_f)xB(E2)\uparrow=56.59 \text{ x } [BR/(1+\alpha)] \text{ x } [\delta^2/(1+\delta^2)]_{*} \text{ x } E(\gamma)^{-5} \text{ x } [(2J_f+1)/(2J_i+1)]$$

n ENSDF, in addition to presenting the absolute measured B(EL)↑ and B(ML)↑ values, the ansition probabilities B(EL)↓ and B(ML)↓ are given in Adopted Gammas in terms of Veisskopf single particle units. For an E2+M1 γ one has

$$B(E2)(W.u.)=9.527x10^6 \text{ x } [BR/(1+\alpha)] \text{ x } [\delta^2/(1+\delta^2)]_{*} \text{ x } E(\gamma)^{-5} \text{ x } A^{-4/3} \text{ x } T½^{-1}$$

$$= 1.6835x10^5 \text{ x } A^{-4/3} \text{ x } [(2J_i+1)/(2J_f+1) \text{ x } B(E2)\uparrow$$

his term is for mult=M1+E2, where δ=|E2/M1|. For E2+M3, where δ=|M3/E2|, this * factor should be replaced by [1/(1+δ²

Coulomb excitation - 3

Explicit relationships for T½xB(L)↑ and B(E2)*(W.u.)* for E1 up to E5 and M1 up to M5 are given in Appendix C of the *Guidelines for Evaluators.*

Note that B(E2)*(W.u.)* can be calculated directly from B(E2). In cases where T½ comes from B(E2), deducing B(E2)(W.u.) from B(E2) rather than through T½ avoids double counting the uncertainty involved in extracting T½.

In cases of higher multipoles, for example E3, M2 and higher from a 0+ gs, where the level halflife is available but the branching to the gs may not be known, the gs branching can be deduced from the appropriate T½xB(L)↑ relationship.

Resonance Fluorescence (γ,γ’) - 1

Resonance fluorescence (NRF), is a tool for exciting low-spin states in even-even nuclei via dipole and quadrupole transitions from the gs. The photon can transfer only a small momentum to the nucleus so the (γ,γ') reaction excites mainly dipole transitions, and to a lesser extent quadrupole transitions. M2 transitions can often be ruled out by use of RUL. The spin selectivity, Jπ=1+, 1-, and with a smaller probability 2+, allows one to study even weak excitations at energies where the level density may be quite high.

Resonance Fluorescence (γ,γ') - 2

NFR experiments usually use bremsstrahlung radiation as a source, with Doppler broadened or Doppler shifted transitions also used. For the Doppler case, one needs to find a readily available transition from some decay or other source that is close in energy to the level one wants to study. The Doppler broadening may then lead to an overlap between the source E_γ and the energy of the excited level. The source should be given in a comment.

Photons with the resonant energy will excite a target with a certain probability which is related to the gs transition width which in turn is related to the transition strength and to the transition matrix elements. These relationships are similar to those discussed earlier in Coulomb excitation.

Resonance Fluorescence (γ,γ') - 3

Example of general comments giving the references and sources

63Fl04	Source = $^{56}Fe(n,\gamma)$,	Eγ=7279
965Gi04	Source = $^{56}Fe(n,\gamma)$,	Eγ=7279, $^{27}Al(n,\gamma)$, Eγ=6980

See 1967Gi15 for a reanalysis of data for the 7279 resonance

967Gi15	Source= $^{56}Fe(n,\gamma)$,Eγ=7279. Reanalysis of data of 1965Gi04
973Sw01	Source = Doppler-broadened 7117 γ from $^{19}F(p,\alpha\gamma)$
974Sw02	Source=bremsstrahlung, E(max)=E(level)+100 keV
978Kn06	Source=variable monoenergetic Compton scattered $^{58}Ni(n,\gamma)$, FWMH=175 keV

e data can be analyzed to determine, in a model-independent way, several quantiti
aracteristic of the excited state.

Resonance Fluorescence (γ,γ') - 4

1. Excitation energies

2. Spin and parity (J from γ(θ) and π if polarized γ's are available or if a Compton polarimeter is used).

3. Decay widths

4. Lifetimes

5. Transition strengths

Resonance Fluorescence (γ,γ') - 5

The most common type of measurement in an NRF experiment is scattering. For the case of photons elastically scattered from a thin target the cross section is proportional to the quantity

$$gW(\theta)\ \Gamma_{\gamma 0}^2/\Gamma \quad [1]$$

Where $g=(2J+1)/(2J_0+1)$, with J=the spin of the excited level and J_0 the gs spin. W is the usual angular correlation function*, and Γ is the total level width**.

For inelastic scattering to a level with J=i, $\Gamma_{\gamma 0}^2/\Gamma$ is replaced by $\Gamma_0\Gamma_i/\Gamma$.

* Measurements are usually done at 127° where W=1 for all dipole transitions independent of the J's

** For levels above particle decay separation energies the particle decay modes should be included. In general, $\Gamma = \Gamma_\gamma+\Gamma_p+\Gamma_\alpha+\ldots$

Resonance Fluorescence (γ,γ') - 6

In the literature authors quote their results in various forms of equation [1]. They usually set W=1, and if J is known then they may also factor in this term, and if they have measured Γ_0/Γ this term is sometimes factored in. The simplest form one finds for equation [1] would thus be Γ_0 or Γ.

If the authors have used quantities that differ from the adopted values of J or ground state branching Γ_0/Γ, then as evaluator one needs to deconstruct the authors' value back to a form from which the appropriate adopted values can be applied.

Resonance Fluorescence (γ,γ') - 7

For example, if the authors quote Γ=0.035 eV 5 but adopted J=2 and the adopted value is 1, then the corrected width would be 0.058 eV *9.* If the authors used Γ_0/Γ=0.823 *24* but the adopted value is 0.886 *16*, then the corrected width would be Γ=0.030 eV *4*. These corrected values are what should be given in the width column.

The width data, in whatever form the authors give, except for total widths, can be put in a re-labeled "S" field.

If the total width can be extracted it should be put in the "T" field, either as Γ or as T½. In adopted levels either width or time units are allowed .

Essential General Comments in Reaction Datasets

1. Reaction with keynumber, unless already included in the ID record
2. Energy of projectile
3. FWHM (full width at half maximum)

Miscellaneous

1. For any reaction with gammas, be sure to include recoil corrections.

$$E_\gamma \text{ (recoil corrected)} = E_{\gamma 0} + (5.3677\times10^{-7} E_{\gamma 0}^2)/A$$

2. In any particle reaction be sure to check the level energies with those from other reactions to see if there is a shift in values. One reaction might show a consistent shift of, say, +5 keV relative to well known values. In another case the level energies might show a shift starting at, say, +5 at 100 keV increasing to +15 at E=2 MeV. In cases such as these a comment is needed stating your observation and adding something like “where used in adopted levels, either included in determining the adopted energy, or in making level associations, these values have been adjusted accordingly”