Structure data in ENSDF from gamma-ray studies in nuclear reactions

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A bit about gamma rays and nuclear reactions

Gamma rays known since 1900: P. Villard: "Sur la réflexion et la réfraction des rayons cathodiques et des rayons déviables du radium," *Comptes rendus*, **130**, 1010-12, ibid 1178-79 (1900).

Named as *gamma* (γ) rays by Rutherford in 1903, as continuation of nomenclature for α and β radiation, gamma rays being most penetrating.

An e.m. transition between two levels of a nucleus. Range can be few keV to ~8 MeV in the nuclear context. Can be lower e.g. 7.6 eV in ^{229}Th. Much higher up to TeV in astronomical context.

Until 1930, about 60 γ rays (emitted by radioactive materials) were known according to:

M. Curie, A. Debierne, A.S. Eve, H. Geiger, O. Hahn, S.C. Lind, S. Meyer, E. Rutherford, E. Schweidler; *The Radioactive Constants as of 1930;* RMP 3, 427 (1931). First compilation of available nuclear data at the time.

Nuclear Reactions have been studied since 1917: $^{14}N + \alpha \rightarrow {}^{17}O + p$ (E. Rutherford)

1942-1943: free neutrons available from reactors

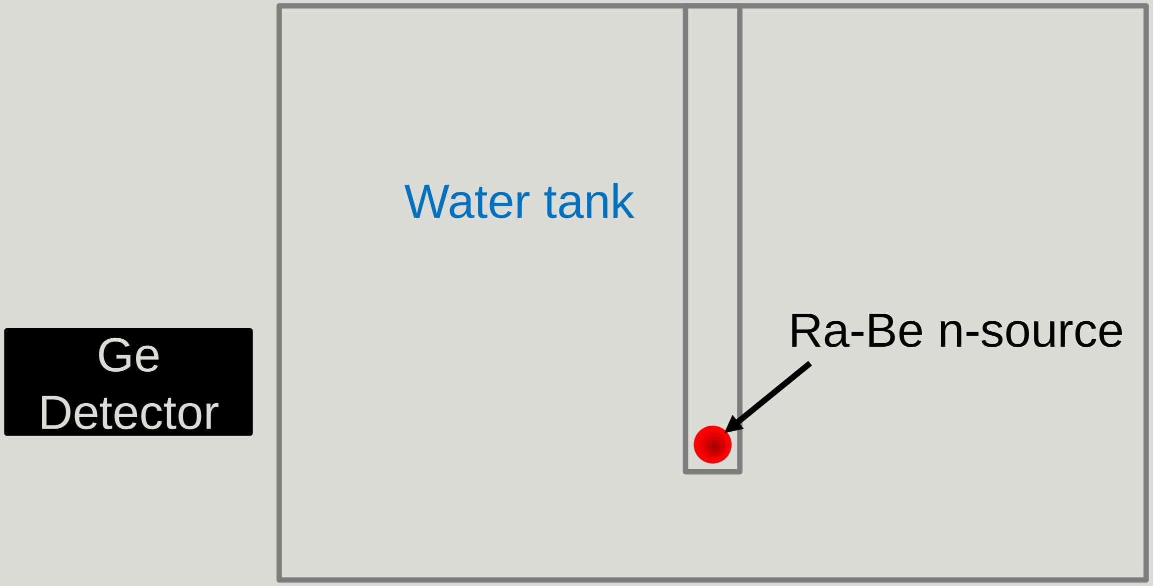
~1950: neutron-capture gamma-ray studies

~1960 and later: neutron scattering, proton, alpha-, and heavy-ion-induced reactions.

Nuclear structure studies using particle beams, and better and bigger gamma-ray detection systems.

Why study gamma rays: detailed decay characteristics of mainly bound levels, e-m transition rates for different multipole orders: offers comparison with theoretical model calculations.

Simple undergraduate lab experiment involving reaction gamma rays



$\alpha + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C^{*} + n$

$n + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + \gamma$ (Leads to deuteron binding energy)

${}^{12}_{6}C^{*} \rightarrow {}^{12}_{6}C + \gamma$ (Doppler shifted; leads to lifetime of the first 2+ state)

Detection of 2224.6-keV gamma from n+H and 4438.0-keV from 12C

ENSDF dataset for 1H(n,γ)

```
2H     1H(N,G) E=THERMAL           1994KI27,1982VA13,1980IS02     ENSDF
2H   H TYP=FUL$AUT=J.H. KELLEY, J.L. GODWIN$CUT=1-May-2003$
2H  c  Target J|p=1/2+.
2H  c  Measured E|g and I|g, deduced S(n)
2H xc  (1994Ki27,1982Va13,1980Is02,1980Gr02).
2H  c  Evaluated S(n)=2224.57 keV (1995Au04).
2H  cL E(A),J(A)$From (1996FiZY)
2H  cG RI        Intensity per 100 neutron captures
2H   N 1
2H  PN
2H   L 0.0         1+               STABLE
2H 3 L FLAG=A$
2H   L  2224.5725220+,1+                                          S
2H  cL J         from s-wave neutron capture
2H   G 2223.245  3 100
2H  cG E         from level-energies difference
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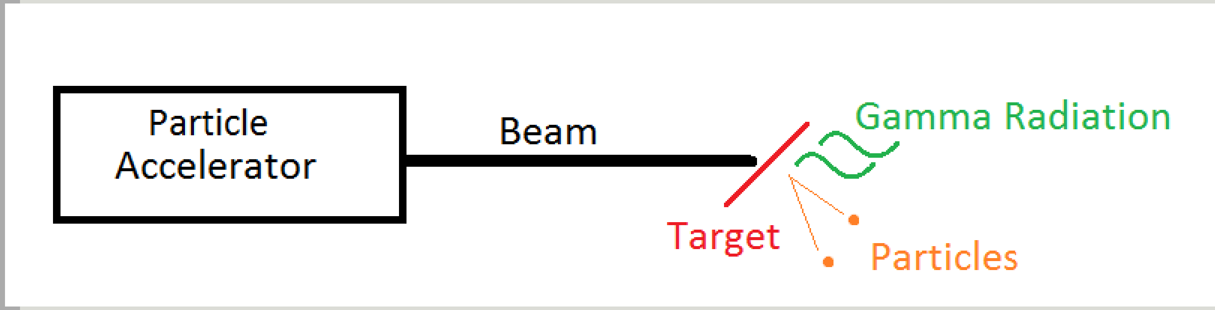
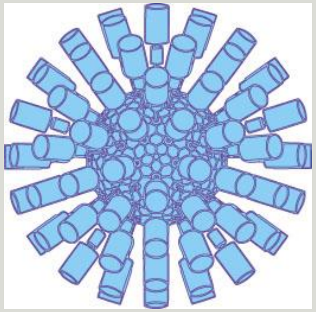
Schematics of in-beam gamma-ray data handling

Gammasphere array





Data Acquisition System (DAQ)

Off-line Analysis

Nuclear Level Schemes and Gamma Ray Transitions

XUNDL, NSR, ENSDF Databases

Gamma rays in nuclear reactions

- Bound states: all kinds of reactions leading to structure information for levels populated in these reactions.
- In-beam gamma-ray studies utilizing light-ion, heavy-ion, deep inelastic scattering, fusion-fission reactions, fission induced by light ions, inverse kinematic reactions for one or two nucleon knockouts, etc.: high-spin structures (Also from prompt γ in SF decay e.g. Cf-252, Cm-248 SF decays)
- Neutron, proton or alpha-particle capture followed by gamma emission: low-spin
- Coulomb excitation: light ion or heavy ion: particle and/or gamma detection: low- and high-spin levels.
- Nuclear-resonance fluorescence: low spin

Nuclear Reactions..

- Inelastic scattering such as (n,n'γ), (p,p'γ), (α,α'γ), etc.: low-spins: gamma and/or particle detection
- Single-particle transfer reactions such as (d,p), (d,t), etc.: low-spins: particle detection; in some of the current experiments, also gamma detection
- Two-particle transfer reactions such as (p,t), (t,p), etc.: low-spins: particle detection; rare gamma detection
- Recoil-decay tagging (RDT), and Isomer spectroscopy: both high- and low-spin levels

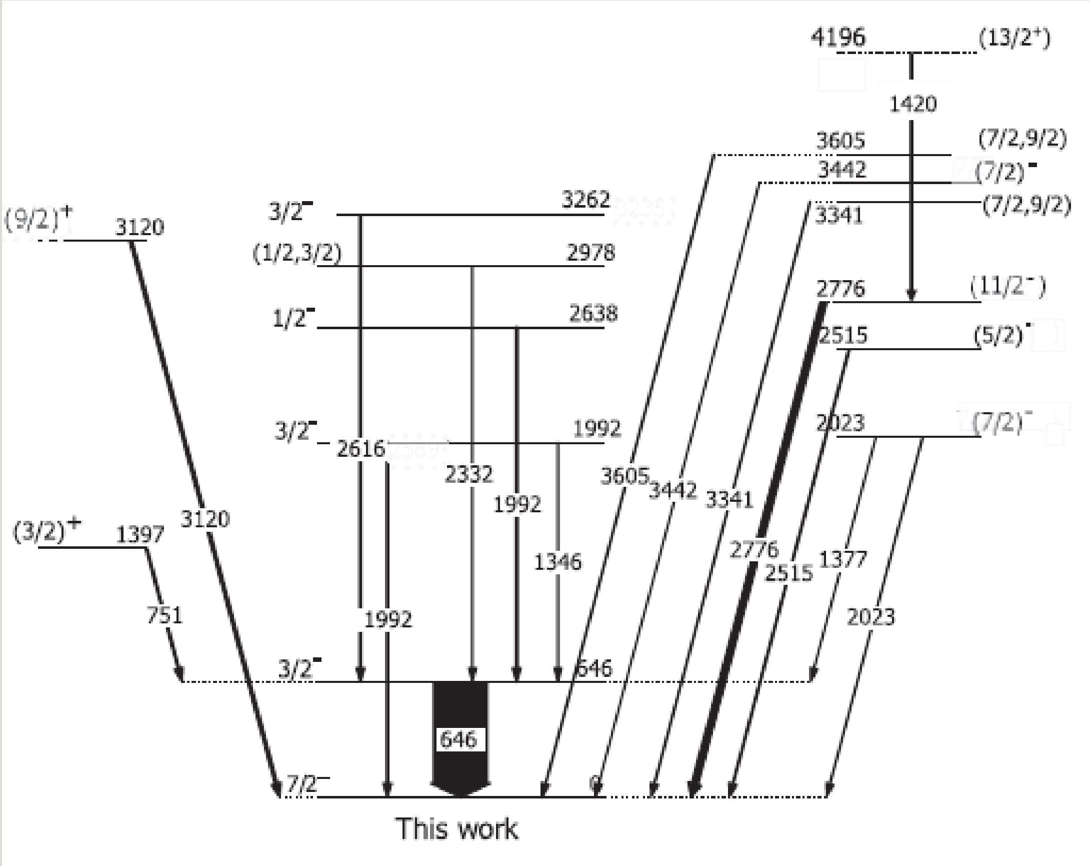
Nuclear Reactions

- Unbound states (resonances): according to recently revised ENSDF policies, inclusion of levels, widths and gamma data for charged-particle resonances (proton, alpha, etc.) is required. Reactions: (p,p), (p,γ), (α, γ), etc. : low-spin. Particle and/or gamma detection.
- E(level) – deduce from S(P)+E(P)(c.m.), where E(p)(c.m.) is deduced from measured E(P) (lab)
- Neutron resonances: (n,γ), (n,n): low-spin: neutron and/or gamma detection. Requirement when final levels are bound, optional otherwise.

^{37}S structure : 2016Ch14: PRC 93, 044318

PRISMA-CLARA set up at INFN, Legnaro

Reaction: 208Pb (36S,37S γ)



^{133}Ce structure: 2016Ay04: PRC 93, 054317

Gammasphere array at ATLAS-ANL. Reaction: 116Cd(22Ne,5n γ)

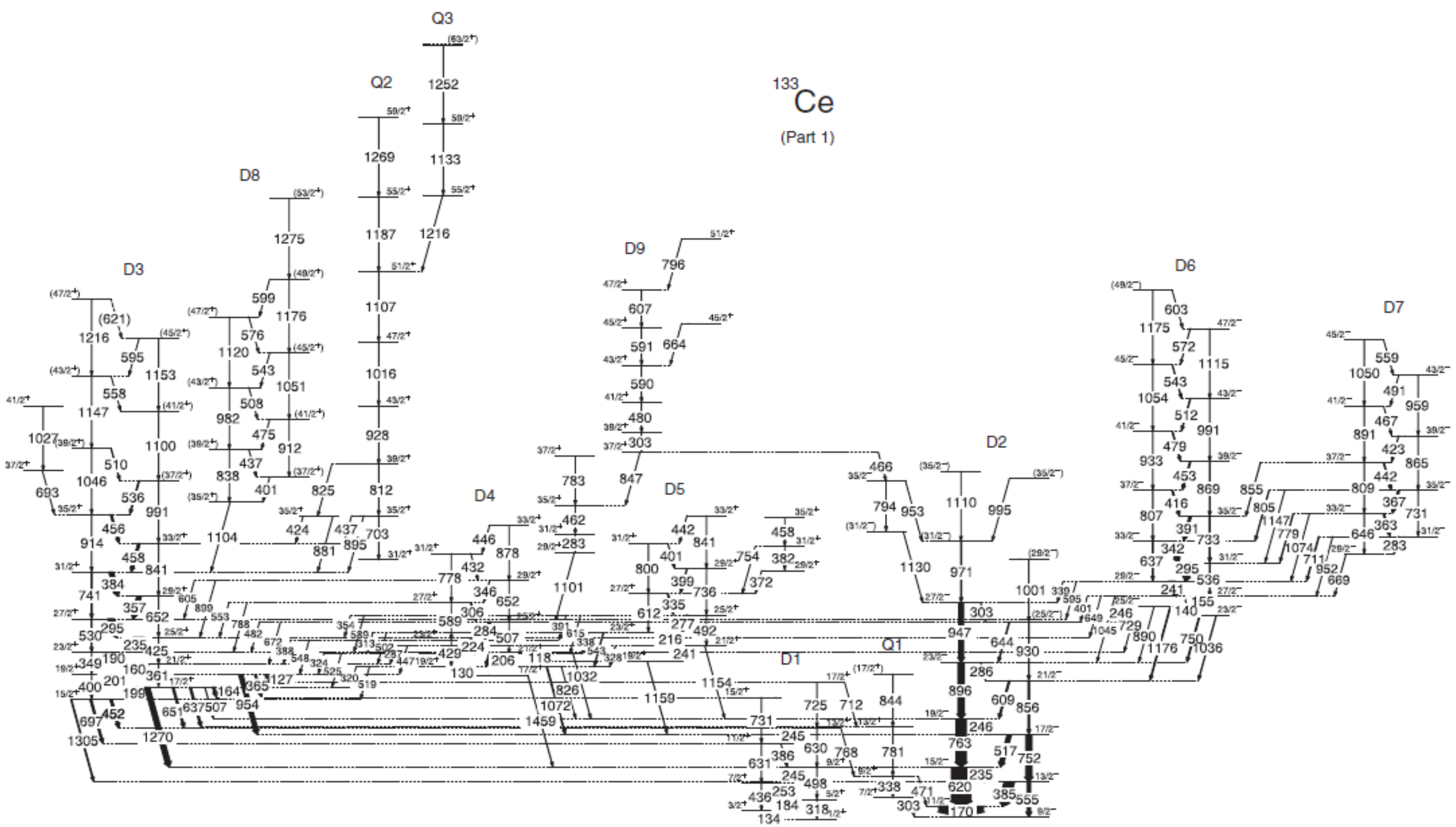


FIG. 1. Part 1 of the level scheme of ^{133}Ce. The widths of the arrows are proportional to the relative intensities of the γ rays.

^{133}Ce structure (contd.)

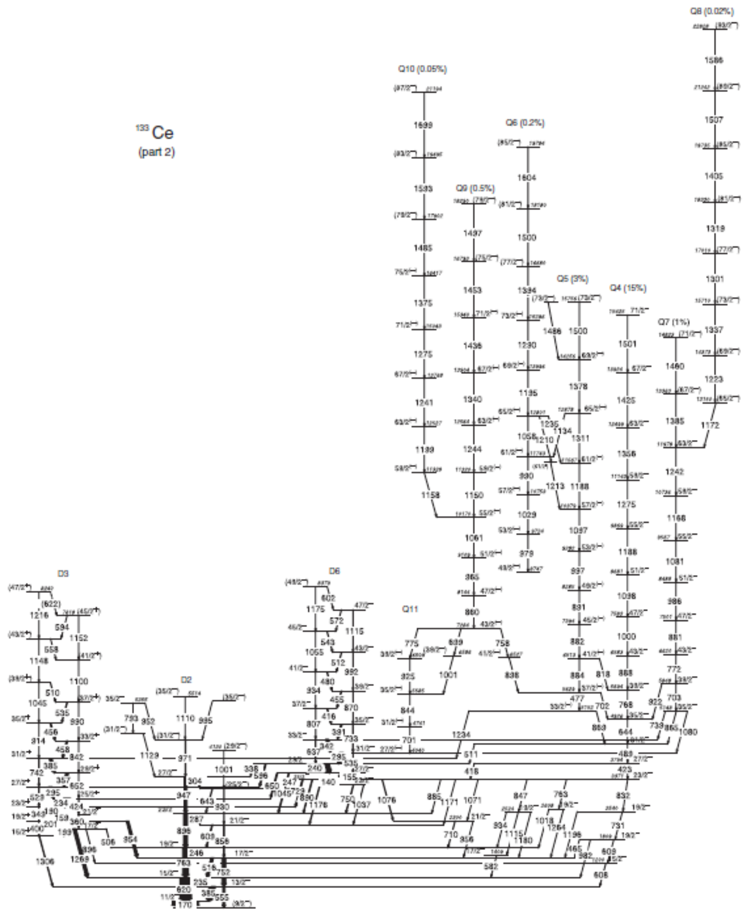


FIG. 2. Part 2 of the level scheme of ^{133}Ce. The widths of the arrows are proportional to the relative intensities of the γ rays. The intensities of the Q bands are given as a percentage relative to that of the yrast band $D2$.

Quantities given in ENSDF
LEVELS

- Energies: deduced from measured gamma-ray energies, and level scheme based on coincidence data (GTOL code used in ENSDF)
- $J\pi$ and T (or T_z) : spin, parity, isospin
- Half-lives: method cited e.g. delayed-gamma, DSAM, RDDS, etc. ($T_{1/2}$ given not the mean lifetime in ENSDF)
- $B(E\lambda)$, $B(M\lambda)$ – transition probabilities e.g. from Coulomb Excitation or NRF
- g factor, μ and Q: static magnetic dipole and quadrupole moments: generally for g.s. and isomers. (Transition quadrupole moments in comments)
- Decay modes for g.s. and isomers.
- Γ, Γ_i – total or partial widths: generally for resonances (or PDR)
- Resonance energies: generally in lab system
- Configurations and/or band structures, band crossings, etc.:

Quantities given in ENSDF
GAMMAS

- E_γ - measured gamma-ray energy (without recoil correction)
- $I\gamma$ - measured relative intensity or branching ratio
- Multipolarity (Mult) and multipole mixing ratio (δ) (Krane-Steffen convention)
- Theoretical conversion coefficient (from BrIcc code) for assigned Mult and mixing ratio.

  (Transitions with E0 admixture or pure E0 need to be handled with care)

  Transition intensity: I(γ+ce): if available or needed.

  γ-γ coincidence evidence: character “C” in column 78 in data file.
- In support of Mult and δ: (information in comments or data-continuation records)
- Measured internal conversion data such as K-, L-shell conversion coefficients, sub-shell ratios (L1/L2/L3..)

  Measured angular distribution/correlation coefficients (A_2, A_4); DCO ratios, Angular asymmetry ratios, Linear polarization coefficients.

  B(Eλ), B(Mλ) – transition probabilities (generally in W.u.)

Nuclear reactions

- To investigate Nuclear shapes, shape co-existence, n-p interaction by experimentally observing nuclear rotational bands with normal deformation, superdeformation and octupole deformation, role of γ deformation and triaxiality, magnetic rotational bands, chirality, signature splitting, backbending, wobbling rotational modes, ….
- Comparison of observed structures with theoretical calculations based on: Cranked Nilsson-Strutinski shell model; Routhians surface contours, large-scale shell-model for low-mass nuclei.

High-spin studies

Since a paper by Morinaga and Gugelot: NP 46, 210 (1963), such data continue to form a large structure data bank in ENSDF.

- Reactions with light ions (p, d, t, ^{3}He, ^{4}He): J<12
- By heavy-ions (A>4): Fusion-evaporation reactions:

  J up to 68 and 141/2. Mostly neutron-deficient nuclei.
- Deep inelastic reactions; one- or two-nucleon knockout reactions in inverse kinematics. (Recent experiments with RI beams). Investigation of *Terra Incognita* (neutron-rich) region
- Since the mid-eighties, large gamma-ray detector arrays: Gammasphere, Eurogam, GASP, SeGA, EXOGAM, MINIBALL, INGA, 8pi, etc. New and more powerful arrays: GRETINA, AGATA. Clovers, Clusters, Segmented HPGe detectors. These are often coupled to particle detection arrays such as MINIBALL, ISIS arrays, etc., and Neutron detectors such as Neutron Wall, MoNA-LISA array, Magnetic spectrometers for conversion electrons

What is measured

- E_γ , Iγ , $\gamma\gamma$-coin , (charged particle, neutrons, ER) γ-coincidences
- 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.
- ADO asymmetry ratio - *e.g.*, I$\gamma(\theta_1)$/I$\gamma(\theta_2)$ in $\gamma\gamma$-coin arrangement
- Linear polarization: polarization asymmetry or IPDCO ratios
- 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
- Quite often details of data from high-spin studies are missing in publications; frequent requests to authors.

What quantities are deduced

- Level energy, spin, parity, lifetime, magnetic moment, transition quadrupole moment, B(M1)/B(E2) or some other reduced transition probability ratios.
- Spins and parities deduced from multipolarities and mixing ratios deduced from angular distribution/correlation data.
  (Krane-Steffen convention in ENSDF for mixing ratio; opposite to Rose-Brink convention)
- Angular Distributions:
- Iγ as a function of angle θ with respect to beam direction:
  - $$\mathbf{W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)+\ldots}$$

  A_2, A_4 as signed values included in ENSDF
- 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.
- For high-spin states, W(θ) is largely independent of J.
- Alignment is reduced or absent if level lifetime is long e.g. micro-sec isomer.
- **W(θ) can determine ΔJ but <u>not</u> Δπ. Need other arguments for parity assignment**

Angular Distributions

Typical values of A_2, A_4 for θ relative to beam direction if $\sigma/J=0.3$

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

Quantities deduced: DCO ratios

- **D**irectional **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 relative to the beam direction:
- 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 Δπ.**
- Gating transitions are frequently stretched quadrupole, but stretched dipole may also be used. Give the character of gating transition
- Remember that almost similar values are expected for stretched quadrupoles and for ΔJ=0, dipole transitions, although the latter are less common.
- Also ADO ratios are commonly seen when count rates are low.
- Such measurements **can determine ΔJ but not Δπ. Need other arguments for assignment of parity.**

DCO Ratios

Typical DCO values for θ_1=37°, θ_2=79°, σ/J=0.3

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

Parity assignment

- L <u>and</u> $\Delta\pi$: from measured subshell ratios or conversion coefficients.
- $\Delta\pi$ may be determined by γ linear polarization measurements.
- When transition strengths can be deduced from measured level lifetimes (or estimated from coincidence resolving times) and branching, **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 reject 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 notation for assumed value: [M1+E2])
- Notes: many authors in papers assign definite MULT even when there are no data to support. In ENSDF, these should not be given
- Ordering of transitions in cascades often disagree: example Pm-139.

In-beam Gamma-ray data

- One data set for each reaction. Mixing relative intensities from different reactions in a single data set is not advised. Also separate datasets for prompt and delayed gamma data.
- Spin-parities are generally taken from original authors' assignments, but in case of differences, comparison should be made with those in Adopted dataset for a nuclide.
- Special care needed in the assignment of multipolarities. In many cases, these may be differently expressed from those given by the authors, or in some others cases, not given at all.
- For level energies, GTOL code is used for a least-squares fit of the gamma-ray data. If reduced chi-squared is high, try to resolve the situation, sometimes by increasing uncertainties or by omitting some gamma-ray energies. GTOL also points out those gamma-ray energies which deviate from the input values. Values which differ by more than 3σ need special attention.

Coulomb excitation with particle and/or gamma detection

- $J\pi$: determined if the excitation probability agrees with that calculated by Alder (1960Al23).
- low energy Coulomb excitation process is expected to be E2
- B(Eλ) with level – for excitation (*i.e.,* B(Eλ)$\uparrow$)
- E2 (or M1) matrix element should be given in comments
- Deduce $B(E\lambda) = |\langle M(E\lambda)\rangle|^2 / (2J_i+1)$ where J_i is initial spin.
- $B(E\lambda; i\to f)\uparrow = B(E\lambda: f\to i)\downarrow \times (2J_f+1)/(2J_i+1))$
- In strongly-deformed region, a cascade of E2 transitions with enhanced transition probabilities ($B(E2)_W > 10$): evidence for a rotational band and for the sequence of $J\pi$ values, provided $J\pi$ of one of the levels is known independently.
- Deduce $T_{1/2}$ from B(Eλ) and adopted γ-branching ratios when possible.
- Mixing ratio can sometimes be extracted from M1, E2 matrix elements. Refer to Reorientation method for quadrupole moment.

Thermal and resonance (ARC) neutron capture studies: (n,γ) E=thermal, (n,γ) E=res

- 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 normalizations.
- 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 or M1 for strong gamma rays; M1+E2 or E2 possible for weaker ones.
- For resonance n capture, it is optional to include the resonances and their properties; it is required to give the bound states fed, their interconnecting gammas and any conclusions concerning level Jπ.
- In average resonance n capture (ARC), include primary and secondary gamma-ray data, and reduced intensities (which carry information on final state Jπ); final bound level energies and deduced Jπ. Also consider authors' statistical analysis using DICEBOX code

Nuclear Resonance Fluorescence: Pygmy dipole resonances and scissors mode excitations: current interest

- (γ,γ) , (γ,γ'), (pol γ,γ') measurements with bremsstrahlung spectrum; low momentum transfer so 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
- Integrated) scattering cross section I_s (eV b) is often given as:
- $I_s = g(\Gamma\gamma_0\Gamma\gamma_f /\Gamma) (\pi\hbar c/E\gamma)^2$, where $g= (2J+1)/(2J_0+1)$, $E\gamma$ in MeV
- where J_0 is g.s. spin, J is spin of excited level, Γ is its total width and Γ_0, Γ_f partial decay widths for γ decay to the g.s. and the final state f, respectively; for elastic scattering, $\Gamma\gamma_0 = \Gamma\gamma_f = \Gamma$. From $g(\Gamma\gamma_0{}^2 /\Gamma)$ and $\Gamma\gamma_0/ \Gamma$ (or $I\gamma_0/\Sigma I(\gamma)$), deduce Γ or level half-life. $T_{1/2}$ (ps)= 0.456 /Γ (meV)
- $B(E1)\uparrow =0.955(g\Gamma\gamma_0/E\gamma^3)$ $[10^{-5}e^2b]$.
- $B(M1)\uparrow =0.0864(g\Gamma\gamma_0/E\gamma^3)$ $[\mu^2_N]$

Inelastic Scattering: (n,n'γ)

- Gamma-ray energies and intensities
- Angular distributions
- Excitation functions and absolute gamma-ray cross sections
- Level lifetimes using Doppler-shift attenuation method.
- Comparison of measured cross sections with theoretical cross sections from EMPIRE or TALYS codes; can lead to spin-parity assignments.

RDT, Isomer spectroscopy: ^{158}Ta: 2016Ca15: PRC 93, 034307

JUROGAM array at University of Jyvaskyla. 102Pd(58Ni,pn γ) reaction

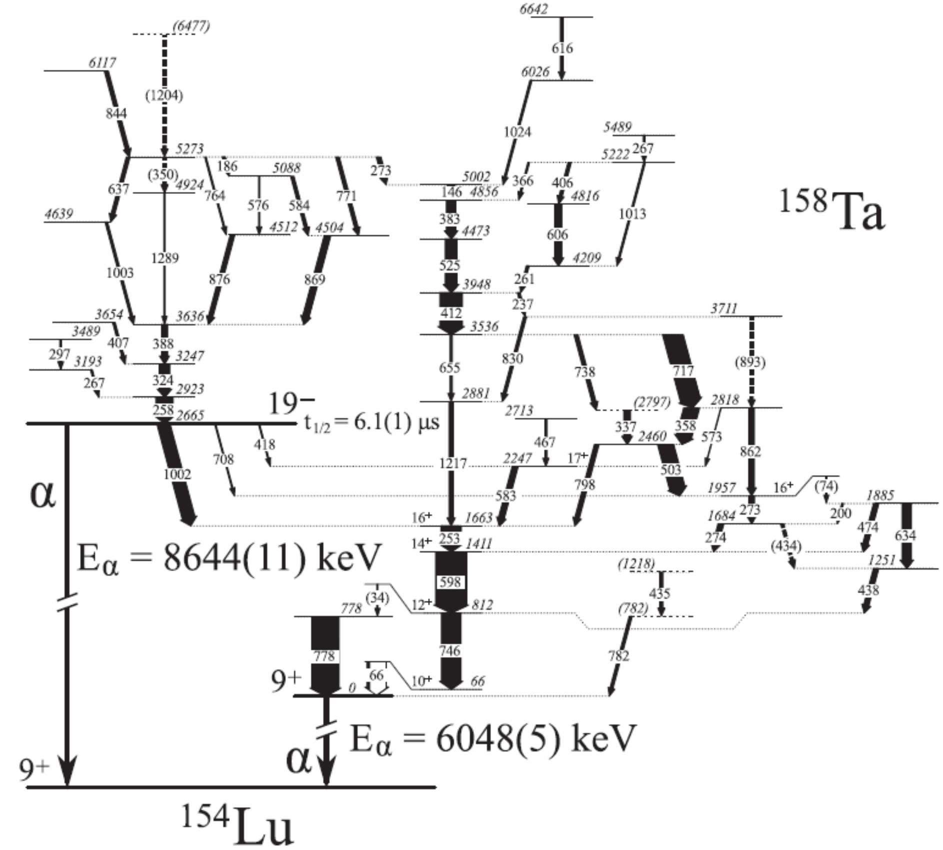


FIG. 3. Proposed level scheme of ^{158}Ta. The widths of the arrows are proportional to the measured intensities in JUROGAM, except for transitions seen only at the focal plane, for which the arrow widths are proportional to intensities measured in the clover detector. Tentative transitions are indicated with dashed arrows with energies in parentheses, while tentative levels are indicated by dashed lines and level energies in parentheses. The α-decay energy of the 9+ state is taken from Ref. [18]. The spin and parity assignments have been adopted from Ref. [16].

Example of an ENSDF-formatted dataset:

^{45}S (Z=16, N=29) single-particle level structure

A. Gade et al. PRC 93, 054315 (May 11, 2016): first study of levels in ^{45}S

```
45S    9BE(46CL,45SG):XUNDL-1        2016GA14                  201607
45S  c  Compiled (unevaluated) dataset from 2016Ga14:
45S 2c  Phys Rev C 93, 054315 (2016)
45S  c  Compiled by B. Singh (McMaster), July 25, 2016
45S  c  One-proton removal reaction from the ground state of {+46}Cl projectile
45S  c  2016Ga14: E({+46}Cl)=86.6 MeV/nucleon produced in
45S 2c  {+9}Be({+48}Ca,X),E=140 MeV/nucleon primary reaction, using A1900
45S 3c  fragment separator at NSCL-MSU facility. Reaction target=376
45S 4c  mg/cm{+2}  {+9}Be. The products were identified using S800
45S 5c  spectrograph based on energy loss and time-of-flight information.
45S 6c Measured particle identification spectra, E|g, I|g using SeGA array of
45S 7c  36-fold segmented HPGe detectors. Deduced levels, J, |p, |s. Detailed
45S 8c  reaction-model, cross sections and spectroscopic factor calculations
45S 9c  for proton-removal reactions using DWBA and SDPF-U and SDPF-MU
45S Ac  shell-model interactions. Calculations assumed J|p=1- for the ground
45S Bc  state of {+46}Cl
45S  cL J$From 2016Ga14, based on shell-model calculations
45S   G  1445     8
45S  cG E$this |g ray is not discussed by 2016Ga14
45S   L 0            (3/2-)
45S  cL $Inclusive |s=2.6 mb {I1} for one-proton removal, derived from
45S 2cL yield of {+45}S reaction products and number of incoming {+46}Cl
45S 3cL projectiles, 5% systematic uncertainty has been added in quadrature
45S   L  506      6  (1/2-)
45S   G  506      6
45S   L 1299      7  (3/2-)
45S   G 1299      7
45S   L 1360      7  (5/2-)
45S   G 1360      7
45S   L 2111      11 (3/2-)
45S   G  751      8
45S   G  809      9                                         ?
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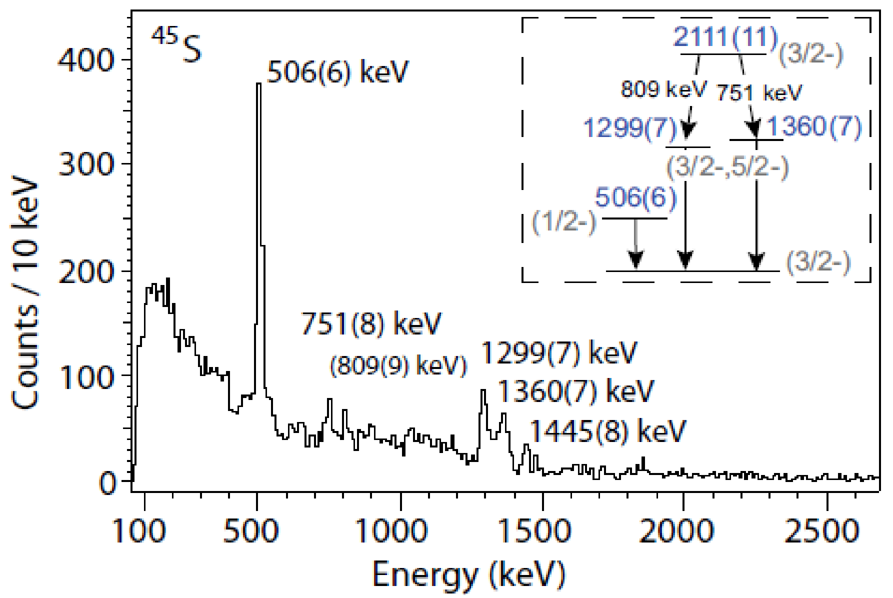


FIG. 6. Event-by-event Doppler-reconstructed γ-ray spectrum of ^{45}S following population of the nucleus in the ^{9}Be(^{46}Cl, ^{45}S $+\gamma$)X one-proton-removal reaction ($v/c = 0.393$). The inset shows a tentative level scheme based on energy sums, intensity arguments, and comparison with shell-model calculations (see text).

Tables, drawing and reference list from the ENSDF-formatted file: using JAVA-NDS code

^{9}Be(^{46}Cl,45sγ):XUNDL-1 2016Ga14

Compiled (unevaluated) dataset from 2016Ga14: Phys Rev C 93, 054315 (2016).
Compiled by B. Singh (McMaster), July 25, 2016.

One-proton removal reaction from the ground state of ^{46}Cl projectile.

2016Ga14: E(^{46}Cl)=86.6 MeV/nucleon produced in ^{9}Be(^{48}Ca,X),E=140 MeV/nucleon primary reaction, using A1900 fragment separator at NSCL-MSU facility. Reaction target=376 mg/cm^2 ^{9}Be. The products were identified using S800 spectrograph based on energy loss and time-of-flight information. Measured particle identification spectra, Eγ, Iγ using SeGA array of 36-fold segmented HPGe detectors. Deduced levels, J, π, σ. Detailed reaction-model, cross sections and spectroscopic factor calculations for proton-removal reactions using DWBA and SDPF-U and SDPF-MU shell-model interactions. Calculations assumed Jπ=1- for the ground state of ^{46}Cl.

^{45}S Levels

E(level)	Jπ†	Comments
0	(3/2-)	Inclusive σ=2.6 mb *1* for one-proton removal, derived from yield of ^{45}S reaction products and number of incoming ^{46}Cl projectiles, 5% systematic uncertainty has been added in quadrature.
506 *6*	(1/2-)	
1299 *7*	(3/2-)	
1360 *7*	(5/2-)	
2111 *11*	(3/2-)	

† From 2016Ga14, based on shell-model calculations.

γ(^{45}S)

E_i(level)	$J_i\pi$	Eγ	E_f	$J_f\pi$	Comments
506	(1/2-)	506 *6*	0	(3/2-)	
2111	(3/2-)	751 *8*	1360	(5/2-)	
2111	(3/2-)	809† *9*	1299	(3/2-)	
1299	(3/2-)	1299 *7*	0	(3/2-)	
1360	(5/2-)	1360 *7*	0	(3/2-)	
		ˣ1445 *8*			Eγ: this γ ray is not discussed by 2016Ga14.

† Placement of transition in the level scheme is uncertain.
ˣ γ ray not placed in level scheme.

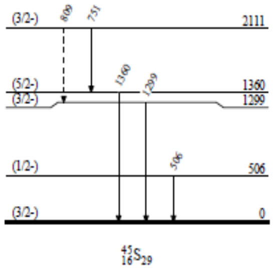
Tables, drawing and reference list

$^{45}_{16}S_{29}$-2 NUCLEAR DATA SHEETS $^{45}_{16}S_{29}$-2

$^{9}Be(^{46}Cl,45s\gamma)$:XUNDL-1 2016Ga14

Level Scheme

Intensities: Relative I(γ)



NUCLEAR DATA SHEETS

REFERENCES FOR A=45

2016GA14 A.Gade, J.A.Tostevin, V.Bader, T.Baugher, D.Bazin, J.S.Berryman, B.A.Brown, C.Aa.Diget, T.Glasmacher, D.J.Hartley, E.Lunderberg, S.R.Stroberg, F.Recchia, A.Ratkiewicz, D.Weisshaar, K.Wimmer - Phys.Rev. C 93, 054315 (2016). *Single-particle structure at N=29: The structure of ^{47}Ar and firstspectroscopy of ^{45}S.*