Berkeley Nuclear Database Projects:

Structure and Decay Data

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Technical Meeting on Nuclear Data Retrieval, Dissemination, and Data Portals
IAEA Headquarters, Vienna, Austria

November 11 – 15, 2024

Table of Contents

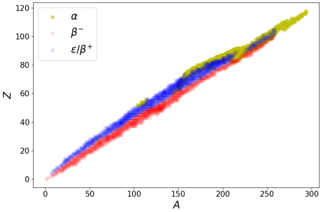
https://nucleardata.berkeley.edu/databases/

Open-source Python library paceENSDF on GitHub

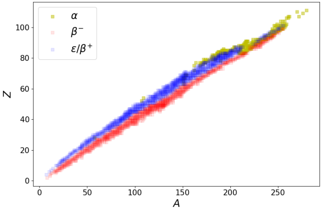
https://github.com/AaronMHurst/pace_ensdf

- *Python Archive of Coincident Emissions from ENSDF*.
- Translated 3254 ENSDF-decay datasets to `JSON` format.
- Converted each ENSDF-decay dataset into RIPL format.
- Generated 2394 JSON-formatted coincidence datasets, i.e., only those containing γ rays.
- Developed suite of Python modules enabling interaction, analysis, and visualization of the **ENSDF-decay** data and derived **coincidence** $\gamma - \gamma$ and $\gamma - X$-ray data.
- Docstrings provided for all methods.
- JSON schema keys documented extensively in `README`.
- 283 unit tests (multiple virtual `Python3` environments).
- Installation, testing scripts, and `Jupyter Notebooks`.
- `JSON` and `RIPL` files bundled with software.
- Over 5000 downloads.

ENSDF decay (all)



ENSDF decay (with γ data)



`git clone https://github.com/AaronMHurst/pace_ensdf.git`

paceENSDF on the Python Package Index (PyPI) repository

https://pypi.org/project/paceENSDF

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paceENSDF 0.4.0

```
pip install paceENSDF==0.4.0
```

Latest version

Released: less than a minute ago

paceENSDF: Python Archive of Coincident Emissions from ENSDF. Package enables interaction, manipulation, analysis, and visualization of radioactive-decay data from the ENSDF archive and corresponding coincidence gamma-gamma and gamma-X-ray emissions.

Navigation

- Project description
- Release history
- Download files

Project links

- Homepage

Statistics

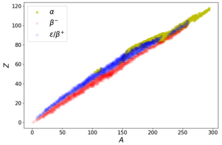
GitHub statistics:

- Stars: 1
- Forks: 0
- Open issues: 0
- Open PRs: 0

View statistics for this project via Libraries.io, or by using our public dataset on Google BigQuery

Project description

The *paceENSDF* (Python Archive of Coincident Emissions from ENSDF) project [HUR2023] is a Python package enabling access, manipulation, analysis, and visualization of the radioactive decay data from the Evaluated Nuclear Structure Data File (ENSDF) library [TUL2001]. A total of 3254 data sets encompassing α (834), $\beta-$ (1141), and $\epsilon/\beta+$ (1279) have been extracted from the ENSDF archive [TUL2001], parsed and translated into a representative JavaScript Object Notation (JSON) format (descibed below). The JSON-formatted data sets constitute a total of 92,264 deexcitation γ rays associated with 41,094 levels. Additionally, we also provide a Reference Input Parameter Library [CAP2008] RIPL-translated format of the corresponding decay-scheme data. These data sets are bundled together with the analysis toolkit. A schematic illustrating the portion of the nuclear chart of relevance to the aforementioned decay data from ENSDF is shown in the figure below.



- pip install paceENSDF
- FreeBSD License

Accessing the decay (α, β^-, and ϵ/β^+) and coincidence ($\gamma - \gamma$ and $\gamma - X$) data using paceENSDF

https://github.com/AaronMHurst/pace_ensdf

```
$ ipython
In [1]: import paceENSDF as pe
In [2]: e = pe.ENSDF()
In [3]: edata = e.load_ensdf() # decay datasets
In [4]: cdata = e.load_pace() # coincidence datasets
```

```
|  load_ensdf(self)
|      Function to assign all 3226 JSON-formatted ENSDF-decay data sets
|      (alpha, beta-minus, electron-capture/beta-plus) to a list object
|      variable.
|  load_pace(self)
|      Function to assign all JSON-formatted coincidence-decay data sets
|      (gamma/gamma and gamma/X-ray) to a list object variable.
|
```

- Run through Jupyter Notebooks from GitHub:
  - Decay data: `decay_paceENSDF.ipynb`
  - Coincidence data: `coinc_paceENSDF.ipynb`

Supporting docstrings for all methods

Example: `help(e.get_levels_and_gammas)` method

```
Help on method get_levels_and_gammas in module paceENSDF.daughter:

get_levels_and_gammas(list, str, index, **kwargs) method of paceENSDF.paceENSDF.ENSDF instance
    Level energies, dexcitation gamma rays, and associated properties
    observed in the residual daughter nucleus following radioactive-decay
    processes according to alpha, beta-minus, and electron-capture/beta-plus
    decay.

    Notes:
        (i) Median-symmetrized values are adopted for gamma-ray mixing
        ratios whereupon asymmetric quantities are encountered in the source
        ENSDF data set.

        (ii) Gamma-ray intensities have not been normalized (i.e., these are
        the raw values from the RI field of the ENSDF Gamma record).  For
        absolute intensities refer to methods from the Normalization class.

        (iii) Total internal-conversion coefficients (where given) are
        calculated values obtained using the BrIcc code:

        [2008Ki07] - T.Kibedi et al., Nucl. Instrum. Methods Phys. Res.
        Sect. A 589, 202 (2008).

    Arguments:
        list: A list of ENSDF-decay data JSON objects.
        str: A string object describing the parent ID.
        index: An integer object associated with the decay index of the
               parent state, where:
               0: Ground-state decay;
               >= 1: Isomer decay.
        kwargs: An additional keyword argument is needed for the appropriate
                radioactive-decay mode:

                mode='A'    : Alpha decay
                mode='BM'   : Beta-minus decay
                mode='ECBP' : Electron-capture/beta-plus decay

                Only the above keyword arguments (case insensitive) are
                acceptable.

    Returns:
        A list object containing levels, gammas, and associated decay-scheme
        properties of the residual nucleus populated following radioactive
        decay.  The list elements are:

        [0]: Level index corresponding to initial level (int);
        [1]: Level index corresponding to final level (int);
        [2]: Associated initial level energy in keV (float);
        [3]: Associated final level energy in keV (float);
        [4]: Number of gammas associated with initial level (int);
        [5]: Index corresponding to gamma-ray number: 0 for first gamma,
             1 for second gamma, etc. (int);
        [6]: Deexcitation gamma-ray energy in keV (float);
        [7]: Deexcitation gamma-ray energy uncertainty (float);
        [8]: Raw gamma-ray intensity (float);
        [9]: Raw gamma-ray intensity uncertainty (float);
        [10]: Gamma-ray multipolarity (str);
        [11]: Gamma-ray mixing ratio (float).  The median symmetrized value
              is given where relevant.
        [12]: Gamma-ray mixing ratio uncertainty (float).  The median
              symmetrized value is given where relevant.
        [13]: Mixing-ratio flag to indicate its sign (int).  Only permitted
              integers are:
              0: No sign given for mixing ratio;
              1: Positive-signed mixing ratio;
              -1: Negative-signed mixing ratio.
        [14]: BrIcc-calculated total internal-conversion coefficient
              (float);
        [15]: Total internal-conversion coefficient uncertainty (float).

    Examples:
        get_levels_and_gammas(edata,"Ra226",0,mode="A")
        get_levels_and_gammas(edata,"Co60",0,mode="BM")
        get_levels_and_gammas(edata,"V50",0,mode="ECBP")
```

```
$ ipython
In [1]: import paceENSDF as pe
In [2]: e = pe.ENSDF()
In [3]: help(e) # Method resolution order
In [4]: help(e.get_levels_and_gammas)
```

Docstrings are provided for all paceENSDF methods with the following general structure:

- Function description.
- Any special notes and/or references.
- Arguments passed to the function.
- What the function returns.
- Examples of function use.

Manipulating the ENSDF levels

Example: Properties of levels in ^{155}Tb following ^{155}Dy ϵ decay

Find isomers in levels following $^{155}\text{Dy} + \epsilon \rightarrow {}^{155}\text{Tb}$

The returned quantities are explained in the docstrings:

```
>>> help(e.find_isomers)
```

The halflife information is returned in its 'best' units or in units of 'seconds' depending on the keyword argument:

```
units = "best"
units = "seconds"
```

In [29]:

```
# Find all isomers in daughter nucleus following radioactive decay ('best' or 's' units for halflife)
isomers = e.find_isomers(edata, "Dy155", 0, mode="ECBP", units="best")
for k,v in isomers.items():
    print("Parent = {0} ({1} keV); Daughter = {2}".format(k[0],k[4],k[5]))
    for vv in v:
        print("index = {0}; energy = {1} \xb1 {2} keV; T1/2 = {3} \xb1 {4} {5}".
              format(vv[0], vv[1], vv[2], vv[3], vv[4], vv[5]))
```

```
Parent = Dy155 (0.0 keV); Daughter = Tb155
index = 0; energy = 0.0 ± 0.0 keV; T1/2 = 5.32 ± 0.06 d
index = 1; energy = 65.4609 ± 0.0024 keV; T1/2 = 0.25 ± 0.03 ns
index = 2; energy = 155.783 ± 0.003 keV; T1/2 = 0.2 ± 0.2 ns
index = 3; energy = 226.916 ± 0.003 keV; T1/2 = 0.35 ± 0.03 ns
index = 4; energy = 250.028 ± 0.004 keV; T1/2 = 0.56 ± 0.05 ns
```

Find levels in ^{155}Tb with multiple J^{π} assignments

In [19]:

```
# Find the levels that have multiple JPi assignments
levels = e.find_multiple_jpi(edata, "Dy155", 0, mode="ECBP")
for k,v in levels.items():
    for vv in v:
        print("index = {0}; energy = {1} \xb1 {2} keV; J = {3}; Pi = {4}".
              format(vv[0],vv[1],vv[2],vv[5],vv[6]))
```

```
index = 11; energy = 508.394 ± 0.019 keV; J = 0.5; Pi = 1
index = 11; energy = 508.394 ± 0.019 keV; J = 1.5; Pi = 1
index = 11; energy = 508.394 ± 0.019 keV; J = 2.5; Pi = 1
index = 12; energy = 517.541 ± 0.015 keV; J = 1.5; Pi = 1
index = 12; energy = 517.541 ± 0.015 keV; J = 2.5; Pi = 1
index = 12; energy = 517.541 ± 0.015 keV; J = 3.5; Pi = 1
index = 19; energy = 861.87 ± 0.07 keV; J = 1.5; Pi = 1
index = 19; energy = 861.87 ± 0.07 keV; J = 2.5; Pi = 1
index = 29; energy = 1452.0 ± 0.03 keV; J = 1.5; Pi = -1
index = 29; energy = 1452.0 ± 0.03 keV; J = 2.5; Pi = -1
index = 30; energy = 1470.98 ± 0.04 keV; J = 1.5; Pi = 1
index = 30; energy = 1470.98 ± 0.04 keV; J = 2.5; Pi = 1
index = 37; energy = 1835.82 ± 0.06 keV; J = 1.5; Pi = 0
index = 37; energy = 1835.82 ± 0.06 keV; J = 2.5; Pi = 0
index = 38; energy = 1860.95 ± 0.07 keV; J = 0.5; Pi = 1
index = 38; energy = 1860.95 ± 0.07 keV; J = 1.5; Pi = 0
index = 38; energy = 1860.95 ± 0.07 keV; J = 2.5; Pi = 0
index = 40; energy = 1868.95 ± 0.05 keV; J = 1.5; Pi = 1
index = 40; energy = 1868.95 ± 0.05 keV; J = 2.5; Pi = 1
index = 43; energy = 1954.72 ± 0.04 keV; J = 1.5; Pi = -1
index = 43; energy = 1954.72 ± 0.04 keV; J = 2.5; Pi = -1
```

Manipulating the ENSDF gammas

Example: γ-ray transitions in ^{155}Tb following ^{155}Dy ϵ decay

```
>>> help(e.get_levels_and_gammas)
```

```
# Levels and gammas associated with daughter following radioactive decay
lg = e.get_levels_and_gammas(edata,"Dy155",0,mode="ECBP")
#for i in lg: print(i)
print("Transition: {0} -> {1}; {2} keV -> {3} keV".format(lg[0][0],lg[0][1],lg[0][2],lg[0][3]))
print("Gamma-ray energy: {0} \xb1 {1} keV".format(lg[0][6],lg[0][7]))
print("Gamma-ray multipolarity: {0}".format(lg[0][10]))
print("Gamma-ray mixing ratio: {0} \xb1 {1}".format(lg[0][11],lg[0][12]))
print("Raw gamma-ray intensity: {0} \xb1 {1}".format(lg[0][8],lg[0][9]))
print("Total ICC: {0}".format(lg[0][14]))
```

```
Daughter nucleus: Tb155 Z=65, A=155
Transition: 1 -> 0; 65.4609 keV -> 0.0 keV
Gamma-ray energy: 65.459 ± 0.003 keV
Gamma-ray multipolarity: M1+E2
Gamma-ray mixing ratio: 0.144 ± 0.005
Raw gamma-ray intensity: 2.68 ± 0.05
Total ICC: 7.58
```

```
subshell = 'calc'
subshell = 'sumcalc'
subshell = 'ratio'
subshell = 'expt'
subshell = 'electron'
```

Refer to the docstrings for more information:

```
>>> help(e.get_levels_and_gammas_subshells)
```

```
# Level and gamma-decay information as before, with additional information for the calculated atomic
# subshell internal conversion coefficients (K to Q shell)
lgs = e.get_levels_and_gammas_subshells(edata,"Dy155",0,mode="ECBP",subshell='calc')
#for i in lgs: print(i)
print("Gamma-ray energy: {0} \xb1 {1} keV".format(lgs[0][6],lgs[0][7]))
print("Total ICC: {0}".format(lgs[0][14]))
print("K-shell ICC: {0} \xb1 {1}".format(lgs[0][16],lgs[0][17]))
print("L-shell ICC: {0} \xb1 {1}".format(lgs[0][18],lgs[0][19]))
print("M-shell ICC: {0} \xb1 {1}".format(lgs[0][20],lgs[0][21]))
print("N-shell ICC: {0} \xb1 {1}".format(lgs[0][22],lgs[0][23]))
print("O-shell ICC: {0} \xb1 {1}".format(lgs[0][24],lgs[0][25]))
print("P-shell ICC: {0} \xb1 {1}".format(lgs[0][26],lgs[0][27]))
print("Q-shell ICC: {0} \xb1 {1}".format(lgs[0][28],lgs[0][29]))
```

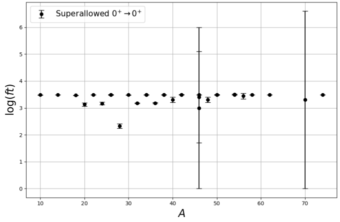
```
Daughter nucleus: Tb155 Z=65, A=155
Gamma-ray energy: 65.459 ± 0.003 keV
Total ICC: 7.58
K-shell ICC: 6.2 ± 0.09
L-shell ICC: 1.072 ± 0.019
M-shell ICC: 0.238 ± 0.005
N-shell ICC: 0.0546 ± 0.001
O-shell ICC: 0.00816 ± 0.00014
P-shell ICC: 0.000464 ± 7e-06
Q-shell ICC: 0.0 ± 0.0
```

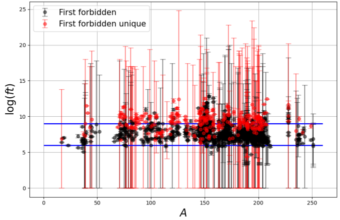
Querying the ENSDF data

Superallowed transitions in ϵ/β^+ and first-forbidden transitions in β^- decay

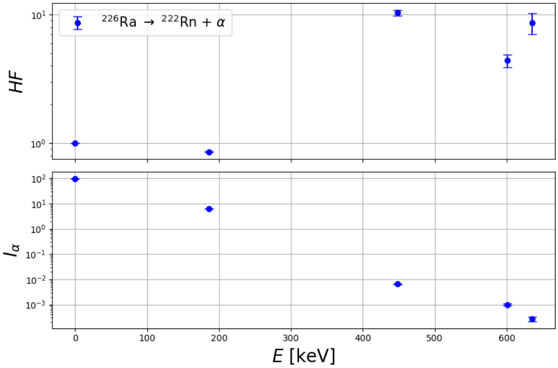
Transition	$\log(ft)$	l
SA	3.5	0
A	$4 - 7.5$	0
1^{st} F	$6 - 9$	1
2^{nd} F	$10 - 13$	2
3^{rd} F	$14 - 20$	3
4^{th} F	≈ 23	4

- Angular momentum selection rules for **firm** J^π assignments.
- Examine trends and anomalies.





Hindrance factors in α decay



- Low-lying levels populated in α decay of ^{226}Ra $\rightarrow$ ^{222}Rn.
- Variance and correlation between I_α and hindrance factors.
- Negative correlation.

$$V = \begin{pmatrix} 14.91 & -80.80 \\ -80.80 & 1368.72 \end{pmatrix}$$

$$C = \begin{pmatrix} 1 & -0.57 \\ -0.57 & 1 \end{pmatrix}$$

Data needed for coincidence calculations

- Each transition is described by 3 quantities: Γ_γ, Γ_e, and Γ_T,

$$\Gamma_T = \Gamma_\gamma + \Gamma_e = \Gamma_\gamma(1 + \alpha), \tag{1}$$

where $\alpha = \Gamma_e/\Gamma_\gamma$ [T. Kibedi, BrIcc (2008)].

- Individual gamma-ray (γ_i), internal-conversion-electron ($\bar{e}_i$), and total transition (T_i) branching ratios (b) are normalized to the sum of all (N) total-transition intensities deexciting a given level:

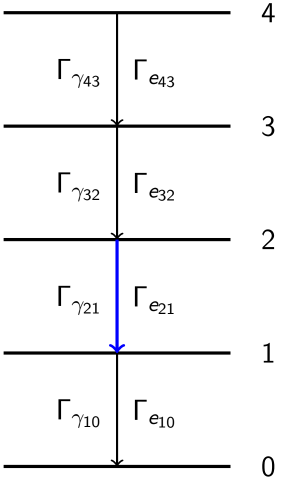
$$b_{\gamma_i} = \frac{\Gamma_{\gamma_i}}{\sum_{i=1}^{N} \Gamma_{T_i}}; \quad b_{\bar{e}_i} = \frac{\Gamma_{e_i}}{\sum_{i=1}^{N} \Gamma_{T_i}}; \quad b_{T_i} = \frac{\Gamma_{T_i}}{\sum_{i=1}^{N} \Gamma_{T_i}}. \tag{2}$$

- K-shell electron contribution for each transition above E_K: $\Gamma_{e_K} = \Gamma_\gamma \alpha_K$.
- X-ray intensity contribution from each $E_\gamma > E_K$, e.g., K_α subshell:

$$I_{XK_{\alpha_i}} = f_{K_{\alpha_i}} \Gamma_{e_K}. \tag{3}$$

where $i = 1, 2$, or 3, and $f_{K_{\alpha_i}}$ is the X-ray BR [R.B. Firestone, *"Table of Isotopes"*, 8th Ed. (1996)]. Total projection $I_{XK_{\alpha_i}}$ is given by sum over all transitions with $E_\gamma > E_K$. Similar for K_β subshell.

Hypothetical decay scheme: Coincidence calculation



EPJ Web of Conferences **284**, 18002 (2023) https://doi.org/10.1051/epjconf/202328418002
ND2022

A decay database of coincident $\gamma-\gamma$ and $\gamma-X$-ray branching ratios for in-field spectroscopy applications

A.M. Hurst[1,*], *B.D.* Pierson[2], *B.C.* Archambault[2], *L.A.* Bernstein[1,3], and *S.M.* Tannous[1]

[1]Department of Nuclear Engineering, University of California, Berkeley, California, 94720, USA
[2]Pacific Northwest National Laboratory, Richland, Washington, 99352, USA
[3]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California, 94720, USA

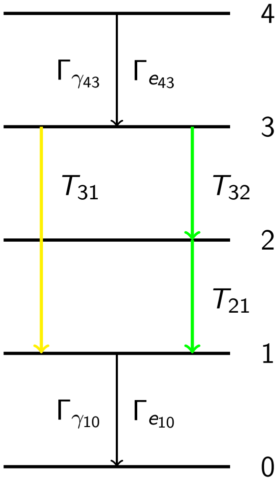
Abstract. Current fieldable spectroscopy techniques often use single detector systems heavily impacted by interferences from intense background radiation fields. These effects result in low-confidence measurements that can lead to misinterpretation of the collected spectrum. To help improve interpretation of the fission products and short-lived radionuclides produced in a composite sample, a coincidence-γ database is being developed in support of a robust portable γ and X-ray coincidence detector system concurrently under development at the Pacific Northwest National Laboratory for in-field deployment. Hitherto, no database exists containing coincident $\gamma-\gamma$ and $\gamma-X$-ray branching-ratio intensities on an absolute scale that will greatly enhance isotopic identification for in-field applications. As part of this project, software has been developed to parse all radioactive-decay data sets from the Evaluated Nuclear Structure Data File (ENSDF) archive to enable translation into a more useful JavaScript Object Notation (JSON) formats that more readily supports query-based data manipulation. The coincident database described in this work is the first of its kind and contains coincidence $\gamma-\gamma$ and $\gamma-X$-ray intensities and their corresponding uncertainties, together with auxiliary metadata associated with each decay data set. The new JSON format provides a convenient and portable means of data storage that can be imported into analysis frameworks with relatively low overhead allowing for meaningful comparison with measured data.

- For each transition: Γ_γ, Γ_e, and Γ_T.
  - $\Gamma_T = \Gamma_\gamma + \Gamma_e = \Gamma_\gamma(1+\alpha)$.
- $\gamma_{21} - \gamma_{ij}$ coincidence intensities:

$$\gamma_{21} - \gamma_{10} = b_{\gamma_{10}} \Gamma_{\gamma_{21}};$$
$$\gamma_{21} - \gamma_{32} = b_{\gamma_{21}} \Gamma_{\gamma_{32}};$$
$$\gamma_{21} - \gamma_{43} = b_{\gamma_{21}} b_{T_{32}} \Gamma_{\gamma_{43}}.$$

- Similar considerations for γ/e_K coincidences.

Hypothetical decay scheme: Coincidence calculation



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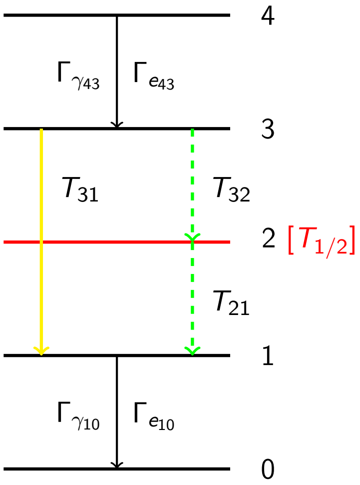
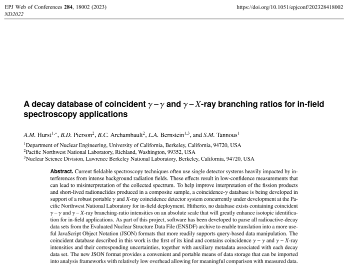
- Two parallel cascade paths between levels 3 and 1:
  1. Path 1: T_{31}.
  2. Path 2: $T_{32} T_{21}$.
- Need to combine parallel paths to correctly determine γ_{10}/γ_{43} coincidence intensity:

$$\begin{aligned}\gamma_{10} - \gamma_{43} &= b_{\gamma_{10}} b_{T_{31}} \Gamma_{\gamma_{43}} + b_{\gamma_{10}} b_{T_{32}} b_{T_{21}} \Gamma_{\gamma_{43}} \\ &= b_{\gamma_{10}} \Gamma_{\gamma_{43}} (b_{T_{31}} + b_{T_{32}} b_{T_{21}}).\end{aligned}$$

Hypothetical decay scheme: Coincidence calculation

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- Impose timecut $T_{1/2}$ [s].
- Transitions through isomer removed from cascade:

$$\gamma_{10} - \gamma_{43} = b_{\gamma_{10}} b_{T_{31}} \Gamma_{\gamma_{43}}.$$

The first database with $\gamma - \gamma$ and $\gamma - X$-ray coincidence energies and intensities

$\gamma - \gamma$ data


```
"decayCoincidences": [
    {
        "gammaEnergyGate": 347.14,
        "gammaEnergyCoincidence": 826.1,
        "unitEnergy": "keV",
        "gammaGateLevelIndexInitial": 3,
        "gammaGateLevelIndexFinal": 2,
        "gammaGateLevelEnergyInitial": 2505.748,
        "gammaGateLevelEnergyFinal": 2158.612,
        "gammaCoincidenceLevelIndexInitial": 2,
        "gammaCoincidenceLevelIndexFinal": 1,
        "gammaCoincidenceLevelEnergyInitial": 2158.612,
        "gammaCoincidenceLevelEnergyFinal": 1332.508,
        "absoluteCoincidenceIntensity": 0.006475000590701808,
        "dAbsoluteCoincidenceIntensity": 0.0007640713835275946,
        "unitIntensity": "percent",
        "numberParallelCascadePaths": 1,
        "coincidenceCascadeSequences": [
            {
                "pathNumber": 0,
                "indexedTransitionSequence": [
                    3,
                    2,
                    1
                ]
            }
        ],
        "gammaGateLevelIsomer": true,
        "gammaGateLevelHalfLifeBest": 3.3,
        "dGammaGateLevelHalfLifeBest": 1.0,
        "unitGammaGateLevelHalfLifeBest": "ps",
        "gammaGateLevelHalfLifeConverted": 3.2999999999999997e-12,
        "dGammaGateLevelHalfLifeConverted": 1e-12,
        "unitGammaGateLevelHalfLifeConverted": "s"
    },
```


$\gamma - X$ data


```
"gammaXrayCoincidences": [
    {
        "gammaEnergy": 1332.492,
        "levelIndexInitial": 1,
        "levelIndexFinal": 0,
        "XrayEnergy": 7.478,
        "labelXrayTransition": "Kalpha1",
        "absoluteCoincidenceIntensityGammaXray": 0.0036023243682508413,
        "dAbsoluteCoincidenceIntensityGammaXray": 0.000172631750774979,
        "unitEnergy": "keV",
        "unitIntensity": "percent"
    },
    {
        "gammaEnergy": 1332.492,
        "levelIndexInitial": 1,
        "levelIndexFinal": 0,
        "XrayEnergy": 7.461,
        "labelXrayTransition": "Kalpha2",
        "absoluteCoincidenceIntensityGammaXray": 0.0018311815538608442,
        "dAbsoluteCoincidenceIntensityGammaXray": 9.363336817623271e-05,
        "unitEnergy": "keV",
        "unitIntensity": "percent"
    },
    {
        "gammaEnergy": 1332.492,
        "levelIndexInitial": 1,
        "levelIndexFinal": 0,
        "XrayEnergy": 8.265,
        "labelXrayTransition": "Kbeta1",
        "absoluteCoincidenceIntensityGammaXray": 0.00043227892419010094,
        "dAbsoluteCoincidenceIntensityGammaXray": 2.0428890285136585e-05,
        "unitEnergy": "keV",
        "unitIntensity": "percent"
    },
```


. . . for every coincidence pair in every decay scheme.

Parallel paths in γ-ray cascades

```
>>> help(e.show_cascades)
```

```
In [3]: # Show the cascade gamma-ray sequence between the 3->2 and 1->0 transitions in 60Ni following
        # 60Co beta-minus decay (G.S.)
        e.show_cascades(cdata,"BM","Co60",0,3,2,1,0)

        Cascade sequence between coincidence gammas: g(347.14 keV)-g(1332.492 keV):
        g(3 [2505.748 keV] -> 2 [2158.612 keV]) - g(1 [1332.508 keV] -> 0 [0.0 keV])

        Path number 1:
        Transition sequence: 3 -> 2: g(347.14 keV) [2505.748 keV -> 2158.612 keV]
        Transition sequence: 2 -> 1: g(826.1 keV) [2158.612 keV -> 1332.508 keV]
        Transition sequence: 1 -> 0: g(1332.492 keV) [1332.508 keV -> 0.0 keV]

Out[3]: [[(3, 2), (2, 1), (1, 0)]]

In [4]: # Show the cascade gamma-ray sequence between the 9->6 and 1->0 transitions in 147Pm following
        # 147Nd beta-minus decay (G.S.)
        e.show_cascades(cdata,"BM","Nd147",0,9,6,1,0)

        Cascade sequence between coincidence gammas: g(53.1 keV)-g(91.105 keV):
        g(9 [685.899 keV] -> 6 [632.85 keV]) - g(1 [91.1051 keV] -> 0 [0.0 keV])

        Path number 1:
        Transition sequence: 9 -> 6: g(53.1 keV) [685.899 keV -> 632.85 keV]
        Transition sequence: 6 -> 3: g(222.27 keV) [632.85 keV -> 410.515 keV]
        Transition sequence: 3 -> 1: g(319.41 keV) [410.515 keV -> 91.1051 keV]
        Transition sequence: 1 -> 0: g(91.105 keV) [91.1051 keV -> 0.0 keV]

        Path number 2:
        Transition sequence: 9 -> 6: g(53.1 keV) [685.899 keV -> 632.85 keV]
        Transition sequence: 6 -> 1: g(541.79 keV) [632.85 keV -> 91.1051 keV]
        Transition sequence: 1 -> 0: g(91.105 keV) [91.1051 keV -> 0.0 keV]

Out[4]: [[(9, 6), (6, 3), (3, 1), (1, 0)], [(9, 6), (6, 1), (1, 0)]]
```

Allows for γ-ray cascade reconstruction and re-calculation of coincidence intensities if required.

Impose timecut on γ ray cascade following ^{99}Mo β^- decay

get_gg_timecut method cf. get_gg method

Remove transitions through the $E = 142.7$-keV ($J^\pi = 1/2^-$) 6-h isomer:

$$t = -21,600\ s$$

```
# Inspecting transient-equilibrium coincidences following 99Mo beta-minus decay.

# To remove coincidences that go through the 6-h isomer at E=142.7-keV (level index=2) impose a 21600-s timecut:

# All coincidences that satisfy timecut:
gg=e.get_gg_timecut(cdata, "BM", "Mo99", 0, -21600)
#for g in gg: print(g[0:12])
print("\nNumber of coincidences = {0}".format(len(gg)))
```

```
Number of coincidences = 54
```

```
# Compare these results with all expected coincidences (i.e. no timecut):
gg=e.get_gg(cdata, "BM", "Mo99", 0)
#for g in gg: print(g)
print("\nNumber of coincidences = {0}".format(len(gg)))
```

```
Number of coincidences = 100
```

```
# Find only coincidences with the 1->0 transition (140.51-keV -> 0-keV) with the same timecut:
gg=e.get_gg_timecut(cdata, "BM", "Mo99", 0, 1, 0, -21600)
for g in gg: print(g[0:12])
print("\nNumber of coincidences = {0}".format(len(gg)))
```

```
[40.58323, 140.511, 1, 0, 140.511, 0.0, 3, 1, 181.0939, 140.511, 0.0, 0.0]
[580.51, 140.511, 1, 0, 140.511, 0.0, 7, 3, 761.95, 181.0939, 0.0, 0.0]
[621.771, 140.511, 1, 0, 140.511, 0.0, 7, 1, 761.95, 140.511, 0.0, 0.0]
[158.782, 140.511, 1, 0, 140.511, 0.0, 8, 7, 920.637, 761.95, 0.0, 0.0]
[739.5, 140.511, 1, 0, 140.511, 0.0, 8, 3, 920.637, 181.0939, 0.0, 0.0]
[242.29, 140.511, 1, 0, 140.511, 0.0, 9, 7, 1004.075, 761.95, 0.0, 0.0]
[822.972, 140.511, 1, 0, 140.511, 0.0, 9, 3, 1004.075, 181.0939, 0.0, 0.0]
[380.13, 140.511, 1, 0, 140.511, 0.0, 12, 7, 1141.862, 761.95, 0.0, 0.0]
[960.754, 140.511, 1, 0, 140.511, 0.0, 12, 3, 1141.862, 181.0939, 0.0, 0.0]
[1001.343, 140.511, 1, 0, 140.511, 0.0, 12, 1, 1141.862, 140.511, 0.0, 0.0]
[410.27, 140.511, 1, 0, 140.511, 0.0, 13, 7, 1172.22, 761.95, 0.0, 0.0]
[1017.0, 140.511, 1, 0, 140.511, 0.0, 14, 3, 1198.88, 181.0939, 0.0, 0.0]

Number of coincidences = 12
```

Include only those transitions through the, e.g., 6-h isomer:

$$t = 21,600\ s$$

```
# Find only coincidences with the 1->0 transition (140.51-keV -> 0-keV) in the path of the 6-h isomer:
gg=e.get_gg_timecut(cdata, "BM", "Mo99", 0, 1, 0, 21600)
for g in gg: print(g[0:12])
print("\nNumber of coincidences = {0}".format(len(gg)))
```

```
[2.1726, 140.511, 1, 0, 140.511, 0.0, 2, 1, 142.6836, 140.511, 0.0, 0.0]
[366.421, 140.511, 1, 0, 140.511, 0.0, 4, 2, 509.125, 142.6836, 0.0, 0.0]
[391.7, 140.511, 1, 0, 140.511, 0.0, 5, 2, 534.44, 142.6836, 0.0, 0.0]
[162.37, 140.511, 1, 0, 140.511, 0.0, 6, 4, 671.5, 509.125, 0.0, 0.0]
[528.788, 140.511, 1, 0, 140.511, 0.0, 6, 2, 671.5, 142.6836, 0.0, 0.0]
[249.03, 140.511, 1, 0, 140.511, 0.0, 8, 6, 920.637, 671.5, 0.0, 0.0]
[411.491, 140.511, 1, 0, 140.511, 0.0, 8, 4, 920.637, 509.125, 0.0, 0.0]
[777.921, 140.511, 1, 0, 140.511, 0.0, 8, 2, 920.637, 142.6836, 0.0, 0.0]
[469.63, 140.511, 1, 0, 140.511, 0.0, 9, 5, 1004.075, 534.44, 0.0, 0.0]
[861.2, 140.511, 1, 0, 140.511, 0.0, 9, 2, 1004.075, 142.6836, 0.0, 0.0]
[537.79, 140.511, 1, 0, 140.511, 0.0, 10, 5, 1072.23, 534.44, 0.0, 0.0]
[457.6, 140.511, 1, 0, 140.511, 0.0, 11, 6, 1129.123, 671.5, 0.0, 0.0]
[620.03, 140.511, 1, 0, 140.511, 0.0, 11, 4, 1129.123, 509.125, 0.0, 0.0]
[986.44, 140.511, 1, 0, 140.511, 0.0, 11, 2, 1129.123, 142.6836, 0.0, 0.0]
[689.6, 140.511, 1, 0, 140.511, 0.0, 14, 4, 1198.88, 509.125, 0.0, 0.0]
[1056.2, 140.511, 1, 0, 140.511, 0.0, 14, 2, 1198.88, 142.6836, 0.0, 0.0]

Number of coincidences = 16
```

```
# Compare these results with all expected coincidences with just the 1->0 transition (i.e. no timecut):
gg=e.get_gg(cdata, "BM", "Mo99", 0, 1, 0)
#for g in gg: print(g)
print("\nNumber of coincidences = {0}".format(len(gg)))
```

```
Number of coincidences = 28
```

- Re-build project using transient-equilibrium data

```
sh installation.sh --transient
```

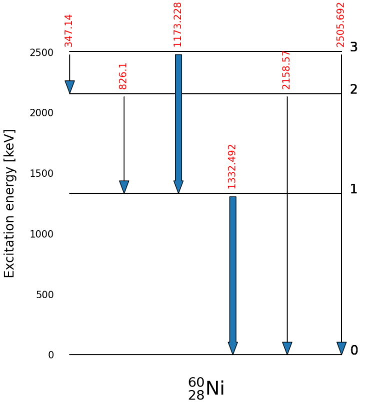
- cf. regular build (see README)

```
sh installation.sh
```

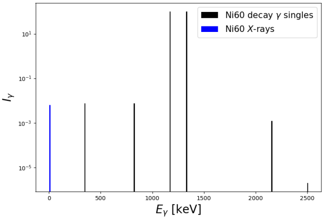
Decay γ-ray emission from radioactive nuclides

Example: ^{60}Co $\rightarrow$ ^{60}Ni + β^- [$T_{1/2}$ = 1925.28(14) d]

Delayed γ rays observed in ^{60}Ni some time after n-interrogation of ^{59}Co: Activation signatures from paceENSDF (*Python Archive of Coincident Emissions from ENSDF*).



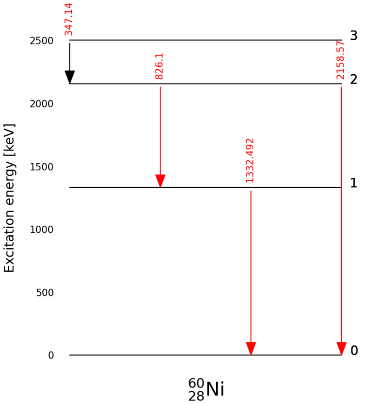
Total projection



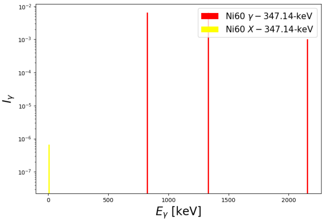
Decay γ-ray emission from radioactive nuclides

Example: ^{60}Co $\rightarrow$ ^{60}Ni + β^- [$T_{1/2} = 1925.28(14)$ d]

Delayed γ rays observed in ^{60}Ni some time after *n*-interrogation of ^{59}Co: Activation signatures from paceENSDF (*Python Archive of Coincident Emissions from ENSDF*).



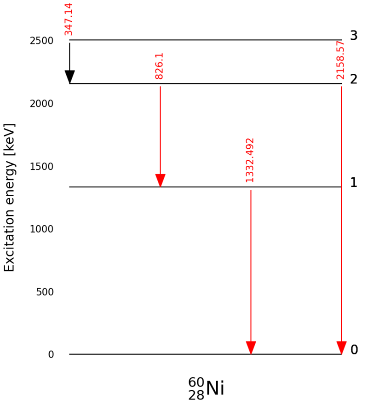
Gate on 3 $\rightarrow$ 2 transition (347 keV)



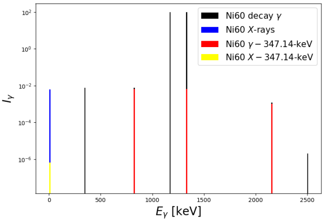
Decay γ-ray emission from radioactive nuclides

Example: ^{60}Co $\rightarrow$ ^{60}Ni + β^- [$T_{1/2}$ = 1925.28(14) d]

Delayed γ rays observed in ^{60}Ni some time after n-interrogation of ^{59}Co: Activation signatures from paceENSDF (*Python Archive of Coincident Emissions from ENSDF*).



"Before" and *"after"*



Forensics applications: Search for $\gamma-\gamma$ and $\gamma-X$-ray pairs

X-ray singles search:

`find_xray`

$\gamma-X$-ray coincidence search:

`find_xray_coinc`

In [33]:
```
# Find all isotopes containing a gamma-X-ray coincidence pair with a 52-keV X ray and 688-keV gamma,
# respectively, assuming the default tolerance=0.5 keV
e.find_xray_coinc(cdata, 52, 688)
```

Out[33]:

	Parent	Decay Index	Ex. Energy	Daughter	Decay Mode	X-ray Label	Photon 1	Photon 2
0	Dy155	0	0.0	Tb155	electronCaptureBetaPlusDecay	Kbeta2	51.698	688.4
1	Tb164	0	0.0	Dy164	betaMinusDecay	Kbeta1	52.113	688.46
2	Tb164	0	0.0	Dy164	betaMinusDecay	Kbeta3	51.947	688.46
3	Lu164	0	0.0	Yb164	electronCaptureBetaPlusDecay	Kalpha1	52.389	687.83
4	Tb170	0	0.0	Dy170	betaMinusDecay	Kbeta1	52.113	687.72
5	Tb170	0	0.0	Dy170	betaMinusDecay	Kbeta3	51.947	687.72
6	Lu170	0	0.0	Yb170	electronCaptureBetaPlusDecay	Kalpha1	52.389	688.0
7	Hf163	0	0.0	Lu163	electronCaptureBetaPlusDecay	Kalpha3	52.443	688.25
8	Lu169	0	0.0	Yb169	electronCaptureBetaPlusDecay	Kalpha1	52.389	687.93
9	Ho157	0	0.0	Dy157	electronCaptureBetaPlusDecay	Kbeta1	52.113	688.1
10	Ho157	0	0.0	Dy157	electronCaptureBetaPlusDecay	Kbeta3	51.947	688.1

In [35]:
```
# Tune the tolerance to narrow the search window to +/- 0.15 keV
e.find_xray_coinc(cdata, 52, 688, 0.15)
```

Out[35]:

	Parent	Decay Index	Ex. Energy	Daughter	Decay Mode	X-ray Label	Photon 1	Photon 2
0	Ho157	0	0.0	Dy157	electronCaptureBetaPlusDecay	Kbeta1	52.113	688.1
1	Ho157	0	0.0	Dy157	electronCaptureBetaPlusDecay	Kbeta3	51.947	688.1

γ-ray singles search:

`find_gamma`

$\gamma-\gamma$ coincidence search

`find_gamma_coinc`

In [37]:
```
# Find all isotopes containing a coincidence pair of gamma rays
# at 106 keV and 392 keV (default tolerance=0.5 keV)
e.find_gamma_coinc(cdata, 106, 392)
```

Out[37]:

	Parent	Decay Index	Ex. Energy	Daughter	Decay Mode	Gamma 1	Gamma 2
0	Cm243	0	0.0	Pu239	alphaDecay	106.47	392.4
1	Np239	0	0.0	Pu239	betaMinusDecay	106.47	392.4

In [38]:
```
# Tune the tolerance to expand the search window to +/- 2.0 keV
e.find_gamma_coinc(cdata, 106, 392, 2.0)
```

Out[38]:

	Parent	Decay Index	Ex. Energy	Daughter	Decay Mode	Gamma 1	Gamma 2
0	La135	0	0.0	Ba135	electronCaptureBetaPlusDecay	107.32	392.08
1	Fr227	0	0.0	Ra227	betaMinusDecay	107.306	391.57
2	Cm243	0	0.0	Pu239	alphaDecay	106.47	392.4
3	Nd133	0	0.0	Pr133	electronCaptureBetaPlusDecay	105.1	393.3
4	Kr90	0	0.0	Rb90	betaMinusDecay	106.05	392.6
5	Kr90	0	0.0	Rb90	betaMinusDecay	106.92	392.6
6	Tl195	0	0.0	Hg195	electronCaptureBetaPlusDecay	107.0	392.2
7	Np239	0	0.0	Pu239	betaMinusDecay	106.47	392.4
8	Mo104	0	0.0	Tc104	betaMinusDecay	105.2	393.1
9	Cs145	0	0.0	Ba145	betaMinusDecay	105.94	391.15

Search methods for single γ rays and X rays also implemented in addition to $\gamma-\gamma$ and $\gamma-X$-ray pairs.

BEApR: BErkeley Alpha and proton Radioactivity

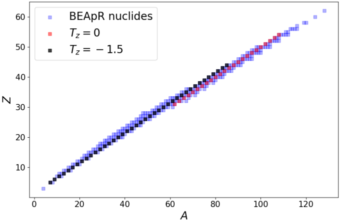
https://nucleardata.berkeley.edu/research/betap.html

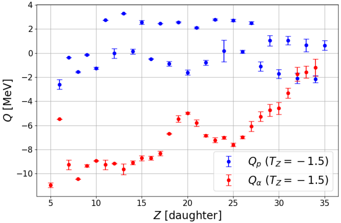
- Led by J.C. Batchelder.
- Work in progress: Downloadable PDFs $-4 \leq T_Z \leq +49/2$.
- Arranged by T_z and Z/A.
- JSON format developed.
- Python project development underway.
- Built up from *many* source datasets, e.g.,


```
"electronCapture": [
    {
        "isEnergeticallyPossible": true,
        "energySystematics": [
            {
                "fromSystematics": false,
                "keyNumber": "2021Wa16",
                "digitalObjectIdentifier": "http://dx.doi.org/10.1088/1674-1137/abddaf"
            }
```


^{39}Ca ϵ decay

[2021Wa16]: M. Wang, W.J. Huang, F.G. Kondev, G. Audi, S. Naimi, *"The AME 2020 atomic mass evaluation"*, Chin. Phys. C 45, 030003 (2021).





Isospin projection $T_z = -3$

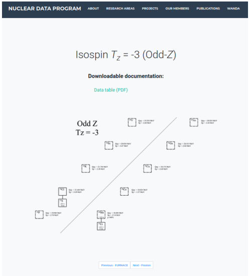


Table 1
Observed and predicted β-delayed particle emission from the odd Z, T_z = -3 nuclei. Unless otherwise stated, all Q-values are taken from [2021Wa16] or deduced from values therein.

Nuclide	J^π	$T_{1/2}$	Q_ε	$Q_{\varepsilon p}$	$BR_{\beta p}$	$Q_{\varepsilon 2p}$	$Q_{\varepsilon 3p}$	$Q_{\varepsilon \alpha}$	Experimental
^{24}P			23.28(50)#	19.98(50)#		19.84(50)#	14.34(50)#		
^{28}Cl			24.20(53)#	21.64(50)#		20.83(50)#	15.32(50)#	15.10(50)#	
^{32}K			24.19(40)#	21.74(40)#		21.47(40)#	16.18(40)#	15.50(43)#	
^{36}Sc			22.60(20)#	20.03(30)#		19.95(30)#	15.29(30)#	15.93(30)#	
^{40}V			21.46(31)#	19.35(30)#		19.95(30)#	15.40(30)#	16.50(30)#	
^{44}Mn		< 105 ns	20.88(30)#	18.09(30)#		17.99(30)#	14.24(30)#	14.03(31)#	**[1992Bo07]**
^{48}Co			19.74(51)#	18.02(66)#		16.62(50)#	11.75(50)#	12.73(50)#	
^{52}Cu			20.68(61)#	18.17(60)#		18.02(60)#	13.87(60)#	13.71(61)#	
^{56}Ga			21.55(64)#	20.51(52)#		20.86(50)#	16.95(50)#	16.30(51)#	
^{60}As			21.89(50)#	20.83(43)#		22.08(40)#	19.80(40)#	17.33(57)#	

Table 2
Particle emission from odd Z, T_z = -3 nuclei. Unless otherwise stated, all Q-values and separation energies are taken from [2021Wa16] or deduced from values therein.

Nuclide	S_p	BR_{1p}	S_{2p}	BR_{2p}	Q_α	Experimental
^{24}P	-2.78(71)#		-1.24(64)#			
^{28}Cl	-1.60(8)*	100%	-2.72(54)#		-8.18(71))#	**[2018Mu18]**
^{32}K	-3.38(45)#		-2.74(40)#		-8.71(64)#	
^{36}Sc	-3.67(36)#		-2.79(36)#		-8.26(50)#	
^{40}V	-2.68(36)#		-2.14(36)#		-6.11(42)#	
^{44}Mn	-2.14(36)#	100%**	-0.50(36)#		-7.43(42)#	**[1992Bo07]**
^{48}Co	-01.57(71)#		0.43(51)#		-8.16(58)#	
^{52}Cu	-2.48(78)#		-1.23(61)#		-6.03(78)#	
^{56}Ga	-3.14(64)#		-2.82(64)#		-4.39(78)#	
^{60}As	-3.44(57)#		-3.32(50)#		-4.23(64)#	

* from [2018Mu18], -3.49(30)# in [2021Wa16].
** Inferred from Half-life.

- All data can be retrieved/downloaded from website in PDF format.
- Disseminate new format in due course.
- Includes Q values and S energies for all known direct and delayed charged-particle emissions with complete listing of refernces.
- Generally different to AME (fine structure to excited states) and ENSDF (update currency).