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TROPIC: A program for calculating reduced transition probabilities ☆

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ABSTRACT

Measurements of level lifetimes and the extracted transition probabilities are one of the cornerstones of nuclear structure physics. The reduced transition probabilities, $B(\pi\lambda; J_i \rightarrow J_f)$ yield information about the structure, wavefunctions, and matrix elements of excited states connected by electromagnetic transitions in a given nucleus. The arsenal of techniques for measuring lifetimes continues to expand and presently includes a wide range of values from femtoseconds to microseconds. While lifetime measurement techniques vary, the extraction of transition probabilities remains the same. RULER is the program used by the National Nuclear Data Center (NNDC) and ENDSF evaluations, while TRANSNUCLEAR was developed at the University of Cologne and modified by a variety of groups. This paper presents a new program TROPIC (*TR*ansiti*O*n *P*robab*I*lity *C*alculator), which is the most modern and efficient way to extract transition probabilities $B(\pi\lambda)$. TROPIC is a program written in Python 3 with the NumPy and SciPy libraries. This is in line with the advances that ENSDF and NNDC are making in moving away from the 80-character card punch input formats. Several design features were implemented to provide a streamlined process for the user and mitigate drawbacks that were present in other programs. The results from TROPIC have been compared with TRANSNUCLEAR and RULER. The answers are as expected identical, but the investment of input to output time is significantly reduced. TROPIC will be made available for public domain use, along with a user guide and example files.

Program summary
Program Title: TROPIC
CPC Library link to program files: https://doi.org/10.17632/958ygp2sb4.1
Developer's repository link: https://github.com/ND-fIREBall/TROPIC
Licensing provisions: GPLv3
Programming language: Python 3
Nature of problem: An efficient way to calculate multiple reduced transition probabilities with minimal effort invested from the user.
Solution method: A Python 3 script has been developed to read in a CSV file containing all necessary input parameters, calculate the transition probabilities listed in the CSV file, and export the results in three different output formats.

1. Introduction

The nucleus is a quantum many body system held together by the strong force. The interactions of the nucleons within the dimensions of the nucleus and the short range of the strong force can result in simple patterns of excited states with lifetimes as short as 10^{-24} s to hours or even years. One way to understand the nature and relationships of the emergent patterns is by the determinations of electromagnetic transition probabilities from measurements of level lifetimes, multipolarities, γ-ray intensities, and conversion coefficients.

Lifetime measurements and the extracted transition probabilities yield information about the relationships between states in a given nucleus. They allow the building and characterization of states in terms of rotational, vibrational, or single particle strengths. The lifetimes of excited states can span a wide range in time and therefore necessitates the implementation and use of a variety of techniques that enable ac-

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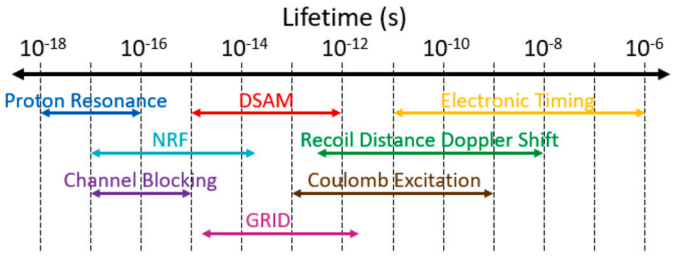

Fig. 1. Lifetime measurement techniques as a function of the associated range in time [1,2].

cess to a given range of time. Fig. 1 shows the experimental methods that have been developed, as a function of accessible level lifetimes, spanning a range in time from 10^{-18} to 10^{-6} s [1]. The Recoil Distance Doppler Shift, Coulomb Excitation, and Electronic Timing methods rely on fast-timing to measure multiple γ-ray and/or particle coincidences to directly obtain the lifetimes of states. In contrast, the Proton Resonance, Nuclear Resonance Flourescence (NRF), and Channel Blocking methods allow the measurements of the partial/total Lorentzian energy width (Γ), from which the lifetime can be extracted. The Doppler Shift Attenuation Method (DSAM) allows the measurement of a unique lifetime-dependent factor from which the level lifetime is obtained. The Gamma-Ray Induced Doppler broadening (GRID) technique [2,3] measures the Doppler broadening of de-exciting γ rays emitted after neutron capture.

Nuclear states can be expressed as eigen wavefunctions of a nuclear force Hamiltonian which are perturbed by the weak and electromagnetic forces. The transition probability ($\mathcal{W}$) is then proportional to the transition matrix element squared connecting the states. The exact relation is obtained by solving the time-dependent perturbed Hamiltonian, which leads to Fermi's Golden Rule:

$$\mathcal{W} = \frac{2\pi}{\hbar}|\langle\psi_f|\mathcal{H}'|\psi_i\rangle|^2\rho(E_f) \tag{1}$$

where ψ_i and ψ_f are the wave functions representing the initial and final states, $\mathcal{H}'$ is the perturbation, and $\rho(E_f)$ is the density of final states.

Below an excitation energy of approximately 10 MeV, the dominant mode of de-excitation is by the emission of γ rays. The transition probability for this de-excitation mode can be expressed as:

$$\mathcal{W} = \frac{8\pi}{\hbar}\frac{(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1}B(\pi\lambda; J_i \to J_f) \tag{2}$$

where $B(\pi\lambda; J_i \to J_f)$ is the reduced transition probability, related to the reduced matrix element of the multipole operator, $\mathcal{O}_{\lambda\mu}(\pi\lambda)$:

$$B(\pi\lambda; J_i \to J_f) = \sum_{\mu M_f}|\langle J_f M_f|\mathcal{O}_{\lambda\mu}|J_i M_i\rangle|^2 = \frac{1}{2J_i+1}|\langle J_f||\mathcal{O}_\lambda||J_i\rangle|^2 \tag{3}$$

Given that $\mathcal{W}$ is also related to the lifetime (τ) of the initial state and the branching ratio (BR) of the transition, Equation (2) can be rewritten as:

$$B(\pi\lambda; J_i \to J_f) = \frac{\hbar}{8\pi}\frac{\mathcal{F}(\pi\lambda)}{\mathcal{G}(\pi\lambda)}\frac{BR}{\tau(1+\alpha)}\frac{\lambda[(2\lambda+1)!!]^2}{(\lambda+1)}\left(\frac{\hbar c}{E_\gamma}\right)^{2\lambda+1} \tag{4}$$

where α is the internal conversion coefficient which is strongly energy dependent. $\mathcal{G}(\pi\lambda)$ is the numerical value of the elementary charge e^2 for $E\lambda$ transitions or the nuclear magneton μ_N^2 for $M\lambda$ transitions to account for the dimensions of $B(\pi\lambda)$. $\mathcal{F}(\pi\lambda)$ is a quantity dependent on the multipole mixing ratio δ for the $\pi(\lambda+1)/\pi\lambda$ components. For pure transitions, $\mathcal{F}(\pi\lambda)$ is 1 while for mixed transitions, it is defined by the expression:

$$\begin{aligned}\mathcal{F}(\pi(\lambda+1)) &= \frac{\delta^2}{1+\delta^2}\\ \mathcal{F}(\pi\lambda) &= \frac{1}{1+\delta^2}\end{aligned} \tag{5}$$

$B(\pi\lambda)$ values yield information about the structure, wave functions, and matrix elements of excited states connected by electromagnetic transitions in a given nucleus. Equation (4) shows that the lifetime of the initial excited state, the relative intensities of the γ-rays depopulating that state, the multipolarity of the transition, and the conversion coefficients of those transitions are important ingredients in calculating transition probabilities.

There are two codes used by the general nuclear science public for calculating $B(\pi\lambda)$ values. The Perl program, TRANSNUCLEAR [4], was developed at the University of Cologne. The National Nuclear Data Center developed and uses RULER [5], a program originally written in Fortran, but recently converted to Java, as part of its ENSDF Analysis and Utility Programs. Both of these programs provide accurate results and have been used for decades. They implemented the best programming tools of the times, but today, they have drawbacks and limitations. TRANSNUCLEAR only calculates probabilities for a single level at a time. It also requires the user to input the information for every transition from a level via prompts on a terminal. Any typographical errors require the user to restart the program and re-input all values from the beginning. RULER mitigates some of these issues by utilizing an input file. The user is able to edit input files and calculate probabilities for multiple levels at once. The main difficulty is the unfriendly format of the input file, which was based on the 80 character punch card input format. While a spreadsheet program can be used to prepare all the input information as a first step, then a second program, Excel2ENSDF [6] is required to convert the input file into the format required for RULER. Furthermore, like TRANSNUCLEAR, the user is required to input all the information for every transition for a specific level for accurate results.

This work reports the development and implementation of a new code TROPIC (*TR*ansiti*O*n *P*robab*I*lity *C*alculator), a program written in Python 3 with the NumPy [7] and SciPy [8] libraries. TROPIC combines the advantages of TRANSNUCLEAR and RULER while mitigating the drawbacks with the goal of making it publicly available and easy to use. The full package will be made publicly available after publication of this manuscript and will include the Python script, a user's guide, and sample files.

2. TROPIC

2.1. Design principles

A few basic principles have guided the design of TROPIC with primary goals of efficiency and user-friendliness. The first, is the decision to write TROPIC in Python 3. Python has increasingly become a prominent language choice in programming due to its easy-to-read syntax. The TROPIC program written in Python makes the main script accessible to anyone interested in reading the source code.

TROPIC allows calculations for large data sets with minimum effort from the user. This is achieved by compiling all input parameters in an input file similar to RULER. However, the input file for TROPIC is a CSV file, which has several advantages. TROPIC's ability to directly read the CSV file eliminates the need for a second program for format conversions. The CSV file can also be presented in a clear, readable format with programs like Excel. The user is able to compile and manage input parameters for multiple transitions of interest all at once.

A list of the parameters is given in Table 1. An example of the input file displayed in Excel containing some transitions in the ^{172}Yb nucleus is shown in Fig. 2 as calculated for Ref. [9]. Each row after the first corresponds to a transition to be calculated while each column contains a parameter required for the calculation. When reading the input file, TROPIC skips the first row to allow the option of labeling the columns

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	A	E_level_(keV)	tau_(fs)	tau_err_up (fs)	tau_err_down (fs)	E_g_(keV)	E_g_err_(keV)	I	I_err	alpha	alpha_err	multipolarity	delta	delta_err_up	delta_err_down	
2	172	78.7427	2380447	72135	72135	78.7426	0.0006	100		8.4		E2				
3	172	260.268	176009	11542	11542	181.528	0.004	100		0.376		E2				
4	172	539.977	23949	2164	2164	279.717	0.005	100		0.092		E2				
5	172	1042.914	4761	1298	1298	964.09	0.05	100				E2				
6								0.173	0.016							E0 transition
7	172	1117.874	5338	577	577	857.636	0.007	100	3			E2				
8						1039.15	0.01	100	3			M1/E2	2.3	0.5	0.3	
9						1117.94	0.03	36	3			E2				
10	172	1405.008	605932	86562	86562	250.035	0.007	6	0.4			E1				
11						287.139	0.003	100	14			E2				
12						1326.1	0.07	88	5			E2				
13								7.2	0.3							E0 transition
14								4.5	0.2							E0 transition
15	172	1476.784	69249	15870	15870	321.82	0.11	0.6	0.16	0.017		E1				
16						1397.92	0.05	100	3			M1/E2	0.8	0.5	0.5	
17								1.22	0.15	0.044						359 keV transition
18								12	2							1216 keV transition
19								36	1							1477 keV transition
20	172	1550.43	5.2E+09	144269504	144269504	174.7	1	100	4	0.079		E1				
21						197.6	0.3	7	1			M1/E2				delta unknown
22						1010.45	0.06	34.8	1.4			E1/M2	-0.38	0.05	0.05	

Fig. 2. Example input file for TROPIC for some transitions in the ^{172}Yb nucleus displayed in Excel. All information was taken from [9]. The first row is used to label the columns. Each row after the first corresponds to a transition while each column lists a parameter of that transition. Details of each parameter are listed in Table 1. Columns after the last column (Column O or $\Delta\delta^-$) can be used to record notes as shown in the figure. Parameters that are not needed or unknown have been left blank. If the mixing ratio of a mixed transition is unknown (as noted for the 1550 keV level), each component is assumed to be pure. Transitions that are not of interest only require the inputs of the γ ray intensity, the internal conversion coefficient, and their respective errors. E0 transitions with known conversion electron intensities can also be included for accurate calculation of branching ratios. This is shown for the 1043, 1405, and 1477 keV levels in the figure.

Table 1
A list of the parameters in the input file. If a parameter is not needed or unknown, the column should be left blank.

Parameter	Description	Units
A	Mass number	-
E_{lev}	Level energy	keV
τ	Lifetime	fs
$\Delta\tau^+$	Upper error on τ	fs
$\Delta\tau^-$	Lower error on τ	fs
E_γ	Energy of emitted γ ray	keV
ΔE_γ	Error on γ ray energy	keV
I	Intensity of emitted γ ray (or conversion electron)	-
ΔI	Error on γ ray intensity (or conversion electron)	-
α	Internal conversion coefficient	-
$\Delta\alpha$	Error on internal conversion coefficient	-
$\pi\lambda$	Multipolarity	-
δ	Multipole mixing fraction	-
$\Delta\delta^+$	Upper error on δ	-
$\Delta\delta^-$	Lower error on δ	-

(as seen in Fig. 2). All columns after the last column ($\Delta\delta^-$) are also ignored, allowing the user to use that space to record notes, comments, or other information. If a parameter is not needed or unknown for a transition (i.e. δ for pure transitions, an unknown α, or uncertainties), the column should be left blank. If the mixing ratio (δ) of a mixed transition is unknown, each component is assumed to be a pure transition and TROPIC calculates the $B(\pi\lambda)$ value for both.

Additional design decisions were implemented to minimize the effort required by the user. TROPIC calculates the branching ratios, requiring the user to only provide the intensities and conversion coefficients in the input file. The only requirement for the format of the intensities is that they are accurately scaled with respect to each other. TROPIC also removes the requirement to include all the individual information for every transition from a level in the input file, allowing the user to obtain calculations for transitions of interest without the full investment of time and effort. After entering all the information on transitions that are of interest in the input file, the user only needs to list the other intensities and conversion coefficients in subsequent rows. If one of the transitions is a pure E0 transition with a known conversion electron intensity (i.e. a E0 transition from a 0^+ state to another 0^+ state), it can also be included in a separate row by listing the intensity as usual and leaving the conversion coefficient column blank. This ensures accurate calculation of the branching ratios. This effort is much less time consuming than recreating the entire, detailed input information required as all other columns in those rows can be left blank.

Table 2
Single Particle Weisskopf values for the ^{172}Yb nucleus using Equation (6).

$\pi\lambda$	Conversion
$E1$	1 mW.u. $= 1.9936\times10^{-5}$ e^{2}b
$E2$	1 W.u. $= 5.6823\times10^{-3}$ e^{2}b^2
$M1$	1 W.u. $= 1.7905\ \mu_N^2$
$M2$	1 W.u. $= 0.5103\ \mu_N^2$b

After preparing the input file, TROPIC can be run from a terminal prompt with a few additional questions asked from the user as shown in Fig. 3. These inputs are for administrative purposes, simply requesting for the input filename, the desired precision of the results, the desired method of error propagation (discussed in detail in Section 2.2), and the desired units (Weisskopf Units or e^{2}b$^\lambda/\mu_N^2$b$^{\lambda-1}$).

Once these inputs are provided, TROPIC automatically calculates the probabilities for all transitions of interest in the input file and provides the results in three ways simultaneously. The first way, presents the results in a text file in LaTeX syntax, which is presented as a table when compiled. The second way, gives the results as a CSV file, allowing them to be displayed in clear, readable format with programs like Excel. The third way, displays the results on the terminal. Examples of the three output methods are shown in Table 3, Fig. 4, and Fig. 5. All results are listed in Weisskopf Units. The Weisskopf Single Particle Estimates are given in Equation (6). Table 2 shows the conversion values calculated for the ^{172}Yb nucleus.

$$B(E\lambda) = \frac{1.2^{2\lambda}}{4\pi}\left(\frac{3}{\lambda+3}\right)^2 A^{\frac{2\lambda}{3}}\ e^2b^\lambda$$
$$B(M\lambda) = 1.2^{2\lambda-2}\frac{10}{\pi}\left(\frac{3}{\lambda+3}\right)^2 A^{\frac{2\lambda-2}{3}}\ \mu_N^2 b^{\lambda-1} \quad (6)$$

```
Enter csv filename (LEAVE OUT file extension): example
Using the input parameters from: /path/to/directory/example.csv
Output files placed at: /path/to/directory/

Enter number of decimal places to report in results (Enter an integer): 2

Enter threshold for propagating errors by using Min/Max method (e.g. enter 0.1 for 10%, leave blank for standard error propagation): 0.1
Using Min/Max method when uncertainty is above 10.0%

Do you want to see the Weisskopf unit conversion? [Y/N]: y
```

Fig. 3. Series of prompts that are asked when TROPIC is run.

Table 3
Results from TROPIC for transitions listed in the input file shown in Fig. 2 displayed as a LaTeX table. All information needed for this output was taken from [9]. All B($\pi\lambda$) values are presented in Weisskopf Units, the unit conversions are shown in Table 2.

A	E_{lev} (keV)	τ (fs)	E_γ (keV)	E_f (keV)	Intensity	α	$\pi\ell$	B($\pi\ell$)
172	78.7427	2380447(72135)	78.7426(5)	0.0	100	8.4	E2	$212.05^{+6.63}_{-6.24}$ W.u.
172	260.268	176009(11542)	181.528(4)	78.74	100	0.376	E2	$300.89^{+21.15}_{-18.55}$ W.u.
172	539.977	23949(2164)	279.717(5)	260.26	100	0.092	E2	$320.75^{+31.89}_{-26.61}$ W.u.
172	1042.914	4761(1298)	964.09(5)	78.82	100	0	E2	$3.62^{+1.36}_{-0.78}$ W.u.
172	1117.874	5338(577)	857.636(7)	260.24	100(3)	0	E2	$2.46^{+0.49}_{-0.39}$ W.u.
			1039.149(10)	78.73	100(3)	0	M1/E2	$3.57e\text{-}04^{+1.82e-04}_{-1.43e-04}$ W.u. (M1 component)
			1039.149(10)	78.73	100(3)	0	M1/E2	$0.79^{+0.21}_{-0.16}$ W.u. (E2 component)
			1117.94(3)	-0.07	36(3)	0	E2	$0.24^{+6.18e-02}_{-4.78e-02}$ W.u.
172	1405.008	605932(86562)	250.035(7)	1154.97	6.0(4)	0	E1	$9.71e\text{-}04^{+3.67e-04}_{-2.48e-04}$ mW.u.
			287.139(3)	1117.87	100(14)	0	E2	$5.9^{+2.79}_{-1.85}$ W.u.
			1326.10(7)	78.91	88(5)	0	E2	$2.47e\text{-}03^{+9.04e-04}_{-6.13e-04}$ W.u.
172	1476.784	69249(15870)	321.82(11)	1154.96	0.60(16)	0.017	E1	$5.47e\text{-}04^{+3.92e-04}_{-2.34e-04}$ mW.u.
			1397.92(5)	78.86	100(3)	0	M1/E2	$6.83e\text{-}05^{+7.51e-05}_{-3.68e-05}$ W.u. (M1 component)
			1397.92(5)	78.86	100(3)	0	M1/E2	$1.01e\text{-}02^{+1.26e-02}_{-8.50e-03}$ W.u. (E2 component)
172	1550.43	5193702147(144269504)	174.7(10)	1375.73	100(4)	0.079	E1	$7.61e\text{-}06^{+1.06e-06}_{-9.22e-07}$ mW.u.
			197.6(3)	1352.83	7(1)	0	M1/E2	$3.71e\text{-}08^{+8.76e-09}_{-7.62e-09}$ W.u. (assumed pure M1)
			197.6(3)	1352.83	7(1)	0	M1/E2	$4.29e\text{-}04^{+1.03e-04}_{-8.92e-05}$ W.u. (assumed pure E2)
			1010.45(6)	539.98	34.8(14)	0	E1/M2	$1.20e\text{-}08^{+1.87e-09}_{-1.64e-09}$ mW.u. (E1 component)
			1010.45(6)	539.98	34.8(14)	0	E1/M2	$7.75e\text{-}06^{+2.99e-06}_{-2.36e-06}$ W.u. (M2 component)

	A	B	C	D	E	F	G	H	I	J	K	L
1	A	E_lev (keV)	tau (fs)	E_gamma (keV)	E_f (keV)	Intensity	ICC	Multipolarity	B(pi*l)	B(pi*l)_err_up	B(pi*l)_err_down	Unit
2	172	78.7427	2380447	78.7426	0	100	8.4	E2	212.05	6.63	6.24	W.u.
3	172	260.268	176009	181.528	78.74	100	0.376	E2	300.89	21.15	18.55	W.u.
4	172	539.977	23949	279.717	260.26	100	0.092	E2	320.75	31.89	26.61	W.u.
5	172	1042.914	4761	964.09	78.82	100	0	E2	3.62	1.36	0.78	W.u.
6	172	1117.874	5338	857.636	260.24	100	0	E2	2.46	0.49	0.39	W.u.
7				1039.149	78.73	100	0	M1/E2	3.57E-04	1.82E-04	1.43E-04	W.u. (M1 component)
8				1039.149	78.73	100	0	M1/E2	0.79	0.21	0.16	W.u. (E2 component)
9				1117.94	-0.07	36	0	E2	0.24	6.18E-02	4.78E-02	W.u.
10	172	1405.008	605932	250.035	1154.97	6	0	E1	9.71E-04	3.67E-04	2.48E-04	mW.u.
11				287.139	1117.87	100	0	E2	5.9	2.79	1.85	W.u.
12				1326.1	78.91	88	0	E2	2.47E-03	9.04E-04	6.13E-04	W.u.
13	172	1476.784	69249	321.82	1154.96	0.6	0.017	E1	5.47E-04	3.92E-04	2.34E-04	mW.u.
14				1397.92	78.86	100	0	M1/E2	6.83E-05	7.51E-05	3.68E-05	W.u. (M1 component)
15				1397.92	78.86	100	0	M1/E2	1.01E-02	1.26E-02	8.50E-03	W.u. (E2 component)
16	172	1550.43	5.2E+09	174.7	1375.73	100	0.079	E1	7.61E-06	1.06E-06	9.22E-07	mW.u.
17				197.6	1352.83	7	0	M1/E2	3.71E-08	8.76E-09	7.62E-09	W.u. (assumed pure M1)
18				197.6	1352.83	7	0	M1/E2	4.29E-04	1.03E-04	8.92E-05	W.u. (assumed pure E2)
19				1010.45	539.98	34.8	0	E1/M2	1.20E-08	1.87E-09	1.64E-09	mW.u. (E1 component)
20				1010.45	539.98	34.8	0	E1/M2	7.75E-06	2.99E-06	2.36E-06	W.u. (M2 component)

Fig. 4. Results of calculations from TROPIC for transitions listed in the input file shown in Fig. 2 displayed in Excel. All information needed for this output was taken from [9]. All B($\pi\lambda$) values are listed using Weisskopf Units, the unit conversions are shown in Table 2.

```
Calculation Results:
-----------------------------------------------------------------------
A: 172 | E_lev (keV): 78.7427 | tau (fs):  2380447.0

Transitions for this level:

E_gamma (keV) | E_f (kev) | Intensity | ICC | Multipolarity | B(pi*l)

78.7426(5) | 0.0 | 100 | 8.4 | E2 | 212.05 +/- (6.63, 6.24) W.u.

-----------------------------------------------------------------------
A: 172 | E_lev (keV): 260.268 | tau (fs):  176009.0

Transitions for this level:

E_gamma (keV) | E_f (kev) | Intensity | ICC | Multipolarity | B(pi*l)

181.528(4) | 78.74 | 100 | 0.376 | E2 | 300.89 +/- (21.15, 18.55) W.u.

-----------------------------------------------------------------------
A: 172 | E_lev (keV): 539.977 | tau (fs):  23949.0

Transitions for this level:

E_gamma (keV) | E_f (kev) | Intensity | ICC | Multipolarity | B(pi*l)

279.717(5) | 260.26 | 100 | 0.092 | E2 | 320.75 +/- (31.89, 26.61) W.u.

-----------------------------------------------------------------------
A: 172 | E_lev (keV): 1042.914 | tau (fs):  4761.0

Transitions for this level:

E_gamma (keV) | E_f (kev) | Intensity | ICC | Multipolarity | B(pi*l)

964.09(5) | 78.82 | 100 | 0 | E2 | 3.62 +/- (1.36, 0.78) W.u.

-----------------------------------------------------------------------
A: 172 | E_lev (keV): 1117.874 | tau (fs):  5338.0

Transitions for this level:

E_gamma (keV) | E_f (kev) | Intensity | ICC | Multipolarity | B(pi*l)

857.636(7) | 260.24 | 100(3) | 0 | E2 | 2.46 +/- (0.49, 0.39) W.u.

1039.149(10) | 78.73 | 100(3) | 0 | M1/E2 | 3.57e-04 +/- (1.82e-04, 1.43e-04) W.u. (M1 component)

1039.149(10) | 78.73 | 100(3) | 0 | M1/E2 | 0.79 +/- (0.21, 0.16) W.u. (E2 component)

1117.94(3) | -0.07 | 36(3) | 0 | E2 | 0.24 +/- (6.18e-02, 4.78e-02) W.u.
```

Fig. 5. Results of calculations from TROPIC for transitions listed in the input file shown in Fig. 2 displayed at the terminal. All information needed for this output was taken from [9]. All B($\pi\lambda$) values are listed using Weisskopf Units, the unit conversions are shown in Table 2.

2.2. Error propagation

TROPIC employs two methods to calculate the uncertainties of the calculated $B(\pi\lambda)$ values associated with the measured lifetimes. The default method is by standard error propagation of all the known errors associated with the various measured input quantities. However, it might be the case that some parameters, usually the lifetimes, will have large uncertainties, sometimes greater than 100%. For those cases, it is more reasonable to use upper and lower bound values of each input parameter to obtain the highest and lowest possible $B(\pi\lambda)$ values and then subtract the upper and lower values from the nominal value to determine the uncertainties. TROPIC prompts the user at the beginning to provide a threshold for the errors in the parameters so that a choice is made on the method for error propagation. For example, if "0.1" is input, TROPIC will automatically switch to using the second "minimum/maximum value" method for error propagation for all transitions that contain a parameter with an uncertainty above 10%. If the user still wishes to use standard error propagation for all transitions, they can do so by submitting a blank input when prompted for the threshold.

2.3. Comparisons with RULER and TRANSNUCLEAR

In order to confirm the accuracy of TROPIC in the development process, its results were compared with those obtained by RULER and TRANSNUCLEAR. Table 4 shows the comparison of the calculated B($\pi\lambda$) values of the three programs with an identical input set from ^{172}Yb [9]. For the nominal transition probability values, there is excellent agreement between TROPIC, RULER, and TRANSNUCLEAR. The small differences are in some of the uncertainty or error calculations, but none of them are outside error limits. These unphysically, tiny differences are due to the method of error propagation used to obtain them. The uncertainties by TROPIC were obtained by using the minimum/maximum value method. The uncertainties by RULER were obtained by using Monte Carlo error propagation, however, it should be noted that the current ENDSF evaluations list uncertainties that were obtained using standard error propagation. The uncertainties by TRANSNUCLEAR were obtained using a combination of standard error propagation and the minimum/maximum value method. When calculating the B($\pi\lambda$) values, TRANSNUCLEAR first combines the mixing ratio (δ) and the Branching Ratio (BR) to obtain an overall scaling factor while using standard error propagation to combine the uncertainties. This scaling factor is then combined with the rest of the parameters (E_γ, α, and τ) to obtain the final B($\pi\lambda$) value. The uncertainties at this point are propagated using the minimum/maximum value method to obtain the final result. This comparison confirms the accuracy of TROPIC and establishes it as a reliable and more user friendly option. TROPIC is a more modern approach to calculating transition probabilities than RULER and TRANSNUCLEAR, getting away from the 80 character punch card format limitations with a significant reduction in effort and time for preparing the input. TROPIC has been used to calculate large sets of B($\pi\lambda$) values in several recent

Table 4
Comparison of B($\pi\lambda$) values calculated by TROPIC, RULER, and TRANSNUCLEAR for selected transitions in ^{172}Yb. All information was taken from [9]. For values written in scientific notation that have symmetric uncertainties, the nominal value and its uncertainties are both listed ($x \pm \Delta x$) before the power of 10. The uncertainties by TROPIC were obtained by the minimum/maximum value method. The uncertainties by RULER were obtained using Monte Carlo error propagation while those by TRANSNUCLEAR were obtained using a combination of standard error propagation and the minimum/maximum value method. All B($\pi\lambda$) values are listed using Weisskopf Units, the unit conversions are shown in Table 2.

E_L (keV)	E_γ (keV)	$\pi\lambda$	B($\pi\lambda$) TROPIC	B($\pi\lambda$) RULER	B($\pi\lambda$) TRANSNUCLEAR
78.7427	78.7426	$E2$	$212.1^{+6.6}_{-6.2}$	$212.1^{+6.7}_{-6.1}$	$213.0^{+6.7}_{-6.3}$
260.268	181.528	$E2$	301^{+21}_{-19}	301^{+21}_{-19}	302^{+21}_{-19}
539.977	279.717	$E2$	321^{+32}_{-27}	321^{+31}_{-26}	322^{+32}_{-27}
1042.914	964.09	$E2$	$3.6^{+1.4}_{-0.8}$	$3.6^{+1.3}_{-0.8}$	$3.6^{+1.4}_{-0.8}$
1117.874.	857.636	$E2$	$2.46^{+0.49}_{-0.39}$	$2.46^{+0.32}_{-0.25}$	$2.47^{+0.38}_{-0.31}$
	1039.149	mixed $M1$	$3.57^{+1.82}_{-1.43} \times 10^{-4}$	$3.57 \pm 1.06 \times 10^{-4}$	$3.57^{+1.07}_{-1.19} \times 10^{-4}$
		mixed $E2$	$0.79^{+0.21}_{-0.16}$	$0.79^{+0.11}_{-0.09}$	$0.79^{+0.33}_{-0.19}$
	1117.94	$E2$	$0.24^{+0.06}_{-0.05}$	0.24 ± 0.03	$0.24^{+0.05}_{-0.04}$
1405.008	250.035	$E1$	$9.71^{+3.67}_{-2.48} \times 10^{-4}$	$9.72^{+1.96}_{-1.50} \times 10^{-4}$	$9.72^{+2.58}_{-1.78} \times 10^{-4}$
	287.139	$E2$	$5.90^{+2.80}_{-1.85}$	$5.91^{+1.06}_{-0.87}$	$5.93^{+1.96}_{-1.47}$
	1326.1	$E2$	$2.47^{+0.90}_{-0.61} \times 10^{-3}$	$2.47^{+0.47}_{-0.35} \times 10^{-3}$	$2.48^{+0.58}_{-0.43} \times 10^{-3}$
1476.784	321.82	$E1$	$5.47^{+3.92}_{-2.34} \times 10^{-4}$	$5.47^{+2.32}_{-1.70} \times 10^{-4}$	$5.47^{+3.50}_{-2.19} \times 10^{-4}$
	1397.92	pure $M1$	$6.83^{+7.51}_{-3.68} \times 10^{-5}$	$6.83^{+3.87}_{-2.78} \times 10^{-5}$	$6.82^{+5.10}_{-3.19} \times 10^{-5}$
		pure $E2$	$1.01^{+1.26}_{-0.85} \times 10^{-2}$	$1.01^{+0.70}_{-0.75} \times 10^{-2}$	$1.02^{+0.76}_{-0.48} \times 10^{-2}$
1550.43.	174.7	$E1$	$7.61^{+1.06}_{-0.92} \times 10^{-6}$	$7.61^{+0.29}_{-0.27} \times 10^{-6}$	$7.61^{+0.65}_{-0.60} \times 10^{-6}$
	197.6	mixed $M1$	$3.71^{+0.88}_{-0.76} \times 10^{-8}$	$3.71 \pm 0.53 \times 10^{-8}$	$3.70^{+0.67}_{-0.63} \times 10^{-8}$
		mixed $E2$	$4.29^{+1.03}_{-0.89} \times 10^{-4}$	$4.30 \pm 0.61 \times 10^{-4}$	$4.31^{+0.80}_{-0.74} \times 10^{-4}$
	1010.45	mixed $E1$	$1.20^{+0.19}_{-0.16} \times 10^{-8}$	$1.20 \pm 0.07 \times 10^{-8}$	$1.20 \pm 0.09 \times 10^{-8}$
		mixed $M2$	$7.75^{+2.99}_{-2.36} \times 10^{-6}$	$7.76^{+1.92}_{-1.74} \times 10^{-6}$	$7.78^{+0.60}_{-0.57} \times 10^{-6}$

publications [10,11]. The goal is for it to become the standard in the field by making it publicly available.

3. Conclusion

There are several popular programs for extracting transition probabilities from the measurements of lifetimes, γ-ray intensities, and conversion coefficients. The two programs are TRANSNUCLEAR and RULER developed and used by various groups to provide a method of calculating B($\pi\lambda$) values. While TRANSNUCLEAR and RULER are great options, they exhibit some drawbacks which are overcome in TROPIC. TROPIC has been developed to provide a modern and streamlined process for the user, offering several advantages over its counterparts. All values calculated from TROPIC are in agreement with those calculated from RULER and TRANSNUCLEAR, confirming its accuracy with easier and less time engagement. Several recent publications have used TROPIC to calculate large sets of B($\pi\lambda$) values from lifetime measurements. The full package will be available for public domain use after the acceptance of this manuscript for publication.

CRediT authorship contribution statement

Kevin Lee: Conceptualization, Project administration, Software, Writing – original draft, Writing – review & editing. **Anne Stratman:** Conceptualization, Software. **Clark Casarella:** Conceptualization, Software. **Ani Aprahamian:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Shelly Lesher:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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