Isomeric Decay of Thallium at the ISOLDE Decay Station

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Abstract: At ISOLDE, proton beams from the Proton Synchrotron Booster are used to induce fission in an Uranium target. These fission fragments are then extracted, mass separated and sent to the ISOLDE Decay Station to study their decay. One such decay is that of nuclear isomers, excited states with a relatively long lifetime. The nuclear isomer of Thallium has a different shape than the ground state, a fascinating phenomenon only known to the atomic nucleus called shape coexistence. This project intends to measure the lifetime of the non-isomeric intermediate state of Thallium to allow us to make inferences about the shape of Thallium in the ground state and the isomeric state.

1. ISOLDE Decay Station

The ISOLDE Decay Station (IDS) is a permanent setup with the purpose to research nuclear structure using decay spectroscopy. The set up used in experiment IS622, the one discussed in this report, includes 24 Germanium detectors arranged in six clovers. The arrangement of these clovers can be seen in Figure 1. [1]

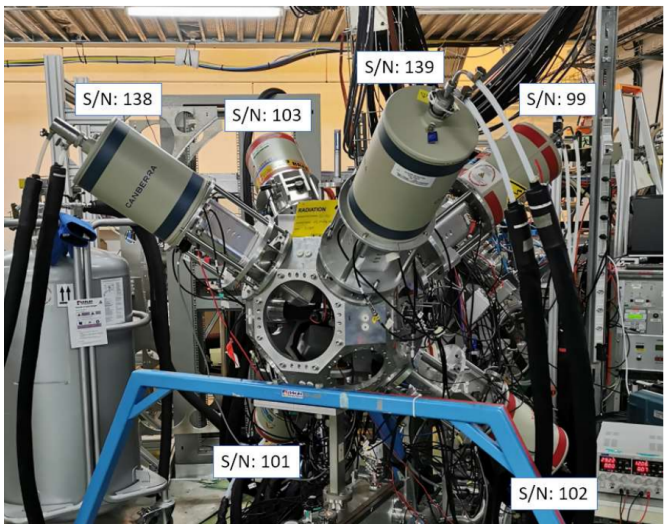

Fig. 1: Clover configuration for IS622

Germanium detectors are used as Germanium is a semiconductor with a very high atomic number, which increases its chance for gamma interaction. Ge detectors have very good energy resolution, and must be kept at very low temperatures with the use of liquid nitrogen in order to reduce noise.

IDS also used 3 Lanthium Bromide crystals (LaBr) to detect gamma rays. These detectors have a lower resolution, but are much faster than the Ge crystals, making them useful for measuring lifetimes.

2. Nuclear Isomers

Nuclear Isomers exist when the nucleus of an atom is in a excited state. Such a state will have a different angular momentum than the states beneath it, and if there is a large difference in angular momentum between the current excited state and the one beneath it, then it will have a long lifetime, making it a nuclear isomer. The angular momentum of the state also determines the multipole of the radiation, as it can be electric or magnetic and a

dipole, quadruple, octupole, etc. When the nucleus decays to a lower state, it emits a gamma ray. This gamma ray, however, sometimes has enough energy to remove an electron from the atom, in a process called electron conversion. The goal of this project is to measure the lifetimes of the excited states of the nucleus, the mixing ratio of the multipolarity, and the electron conversion coefficient for the internal decay of Thallium.

3. Methods and Analysis

3.1. Calibration and Efficiency

Before analysis can begin, the data must properly be calibrated, because measurements of energy from the Ge clovers are in arbitrary units which vary for each crystal. We use Eu_{152} for calibrations as it has a long half-life, around 13 years, a unique spectrum, and decays along a wide range of energies. To begin, the most intense energies and their respective intensities for Eu_{152} are recorded from the National Nuclear Data Base.

Intensity	Energy(keV)
28.53	121.7817
7.55	244.6974
26.59	344.2785
2.237	411.1165
2.827	443.9606
12.93	778.9045
4.23	867.38
14.51	964.057
10.11	1085.837
13.67	1112.076
20.87	1408.013

Then the most prevalent peaks from each crystal are fitted with a Gaussian curve on a second order background, as seen in Figure 2. The means of the peaks are then compared to the known energies, and a linear fit is created between them to be used for calibration. To check the accuracy of this calibration, the residuals of the fit are then plotted. Most residuals had a value less than 0.04 , indicating a successful calibration. Crystal 11, however, is notably missing one of the most intense energies at 121keV. Due to this error, we have decided to remove crystal 11 from our analysis.

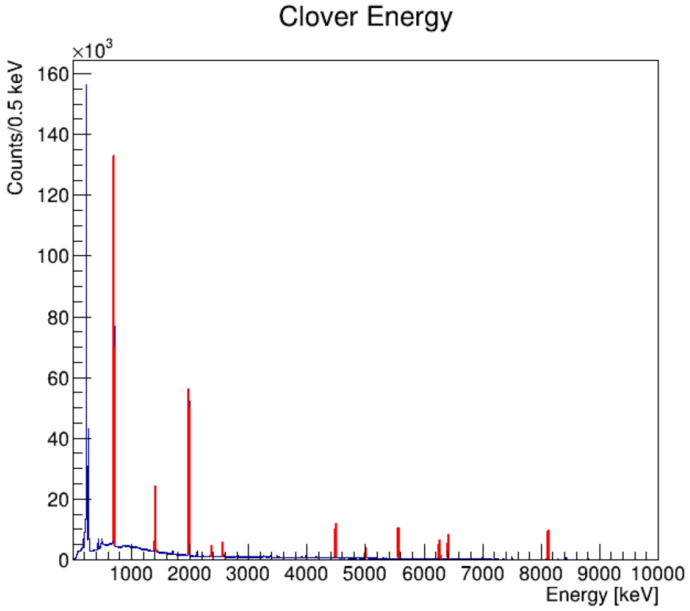

Fig. 2: Energy Spectrum for Crystal 0

After calibration, the energy from all of the clovers is analyzed together. The efficiency for is then calculated using $\varepsilon = a/(I \cdot \Delta t \cdot A)$ where I is intensity, a is area of the peak, Δt is the time of the run, and A is the activity of the Eu_{152} source at the time of the run. The activity is calculated by $A = A_o \cdot e^{-t \cdot \ln 2/t_{1/2}}$. The efficiency is also

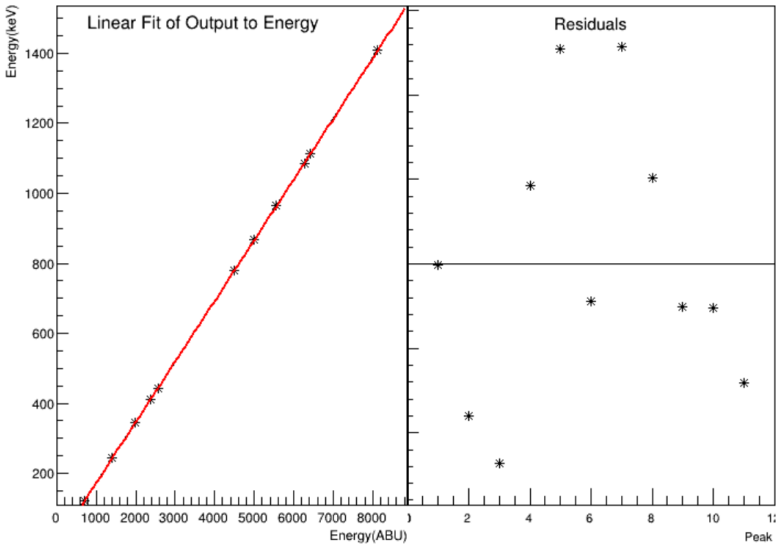

Fig. 3: Fit for Calibration and Residuals for Crystal 0

scaled for the size of the binning, which is 0.5keV/bin. In order to interpolate the efficiencies of other energies, the data is then fit using the equation $\varepsilon = (A + B \cdot \ln E \cdot C \cdot \ln E^2 + C \cdot \ln E^3 + D \cdot \ln E^4)/E$. The efficiencies and this fit can be seen in the figure below.

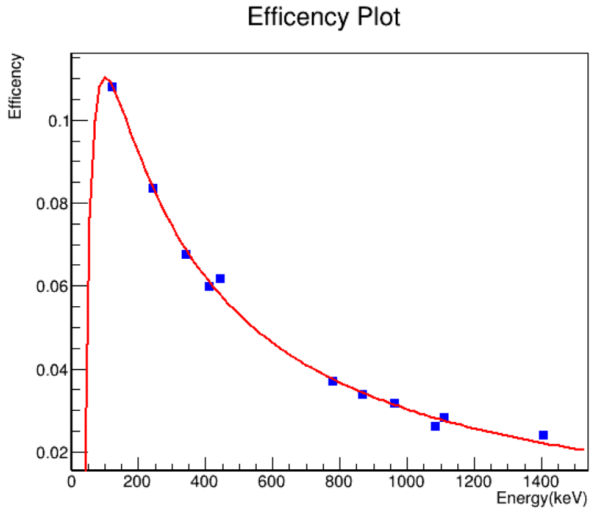

Fig. 4: Efficiency for Ge Detectors

These where calculated to be absolute efficiencies, but they do not match previous efficiencies of the Germanium crystals calculated using Eu_{152}, so we will create relative efficiencies using these values.

The LaBr crystals must also be calibrated, although not as precisely as the Ge crystals. Using data from Run 145, another Eu_{152} run, the same methodology was used to calculate the calibrations. The figures below show the linear fit of the LaBr output to energy, as well as the residuals of this fit. While there is notably high residual for one of the larger energies, this is not of much concern as the energies we are analyzing are much lower, where the fit is much better.

The values needed to calibrate the TACs used in this analysis were obtained from the IS622 elog. The data entered into the final calibration final can be seen in the table below.

Detector	Module	Channel	a_0	a_1	a_2	a_3
Clov0	0	0	-0.510489	0.173322	0	0
Clov1	0	1	-0.201745	0.176631	0	0
Clov2	0	2	-0.0563338	0.174658	0	0
Clov3	0	3	-0.216609	0.171544	0	0
Clov4	0	4	-0.076994	0.187442	0	0
Clov5	0	5	0.0539404	0.186945	0	0
Clov6	0	6	-0.250924	0.185068	0	0
Clov7	0	7	-0.316977	0.18104	0	0
Clov9	0	8	0.654069	0.181371	0	0
Clov10	0	9	0.473178	0.178451	0	0
Clov11	0	10	0.0847713	0.168633	0	0
Clov12	0	12	0.380973	0.173653	0	0
Clov13	0	13	0.495438	0.171882	0	0
Clov14	0	14	-0.2114	0.17221	0	0
Clov15	0	15	-0.293405	0.171564	0	0
Clov16	1	0	0.0482345	0.190562	0	0
Clov17	1	1	-0.591754	0.184786	0	0
Clov18	1	2	-0.219952	0.19096	0	0
Clov19	1	3	-0.261468	0.191096	0	0
Clov20	1	4	-0.397062	0.182607	0	0
Clov21	1	5	-0.789559	0.181112	0	0
Clov22	1	6	-0.480349	0.182415	0	0
Clov23	1	7	-0.757651	0.178734	0	0
TAC La3-La1/2	1	8	0	0.7457069	0	0
TAC	1	9	0	0.7391212	0	0
TAC	1	10	0	0.7365949	0	0
TAC La1-La2	1	11	0	0.7247823	0	0
LaBr1	2	3	6.73424	0.0729388	4.9774e-07	0
LaBr2	2	4	-9.04642	0.0681891	7.21493e-07	0
LaBr3	2	5	-0.495834	0.102476	5.56499e-07	0

3.2. Analysis of Thallium

The odd neutron-deficient Thallium masses we are studying this experiment decay from a nuclear isomer with a gamma that has a pure E3 multipole, and then from the intermediate state to the ground state with either a M1 or E2 multipole. In this section, we determine the mixing ratio, which tells us which proportion of the decays are E2 or M1, and the electron conversion coefficent. To do this, we construct a gamma-gamma matrix from the clovers. This matrix is only filled if the time difference between two measurements in different clovers is less than the coincidence time. The coincidence time is determined by plotting the time difference between readings in the different clovers during the same event. The figure below shows the plot of these time differences.

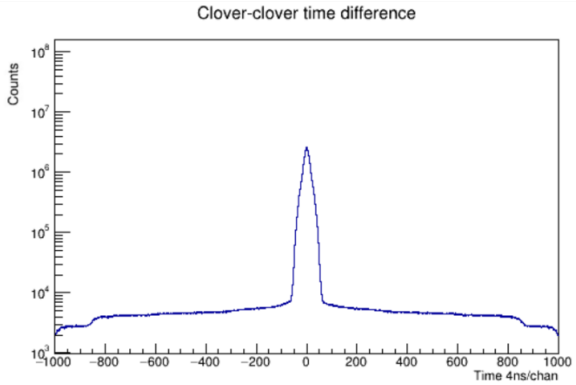

Fig. 5: Time Difference Between Clovers

The width of the peak corresponds to the coincidence time, which the background in random for all other times. For this expierement, we set the coincidence time for 50ns. I used the window between -500 to -100 and 100 to 500ns to create a gamma-gamma matrix with random time. These matracies were then normalized with respect to time and subtracted to create a gamma-gamma matrix without a time-random background. Below is a figure which shows the result of this gamma-gamma matrix.

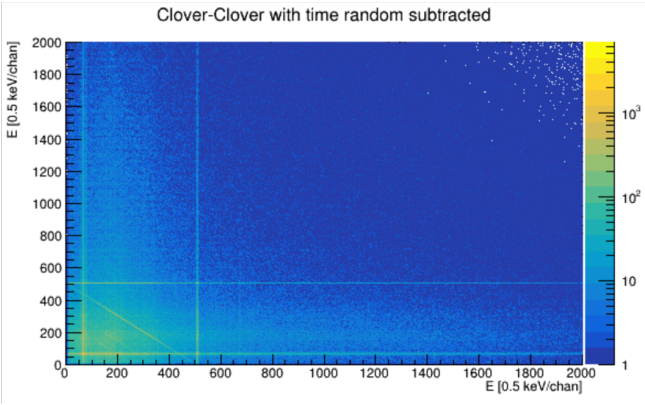

Fig. 6: Gamma-Gamma matrix using Clovers

We then used data from NuDat to find the internal decay of Thallium for the following masses, 181, 183, 185, and 187. Analysis could not be completed for Tl_{181}, the lifetime of the decay was not long enough to be measured by out detectors, and for Tl_{187} because the initial decay was a gamma of 35keV, which our detectors have very low efficiency for, and most of this gamma ray was used for electron conversion, so it could not be detected. The decays for the two masses used in this analysis are listed in Table 2.

Mass	Energy of 1st Decay(keV)	Energy of 2nd Decay(keV)
183	227	335
185	168.8	284

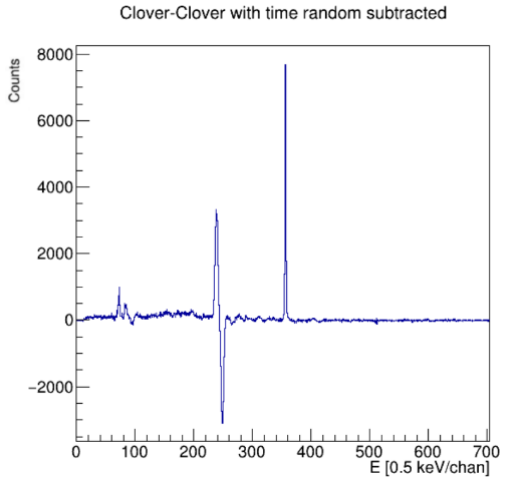

Fig. 7: Projection gated around 272keV for Tl_{183}

The gamma-gamma matrix is gated around the energy of the first decay to create a projection of coincidence gammas. A projection of the nearby Compton background is also created to subtract from the first projection and isolate the gammas. The results of such a projection are shown in Figure 7. In this step, we check that the there is a peak in the energy of the gamma from the second decay, confirming that these decays are in coincidence, and that there is not a peak in the energy we gated around. This would indicate our results are being skewed by a separate decay of the same energy.

Next, we want to find the intensities of these peaks. However, we know some of the gammas are being lost to electron conversion so we must find the electron conversion coefficient. The equation for intensity is given by $I = I' * (1 + \alpha)$, where I' is the area of the peak in our fit divided by the efficiency of our detectors at that energy, and α is the electron conversion coefficient. As the first decay is a pure E3, the electron conversion coefficient can be found using the BRICC database. The coefficients for the two masses are listed below.

Energy(keV)	Electron Conversion Coefficient	Mixing Ratio
183	0.2989	1.5
185	8.670	0.7

We can conclude, because there are only two gammas produced in this internal decay, the intensity of the first and second decay should be equal. Using this, we can solve for the electron conversion coefficient of the second decay. Knowing the ECC, when can retrieve the mixing ratio from the BRICC database. This result varies depending on the range used to fit the peaks.

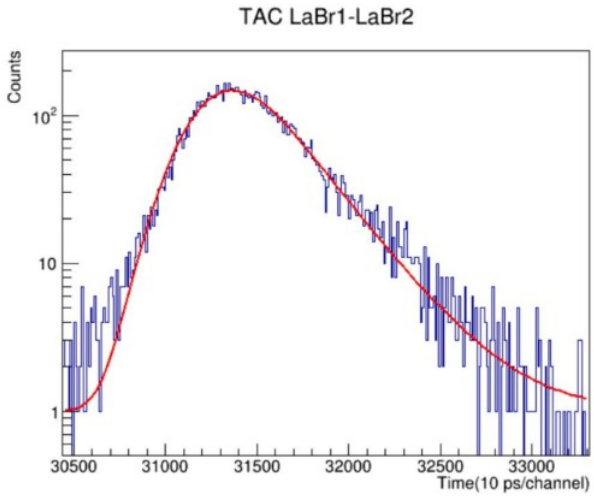

Fig. 8: Convoluted Gaussian Projected into TAC

Next, we measure the lifetime of the nuclear isomer and intermediate state using the LaBr crystals. First, we find gamma rays that are in coincidence with between LaBr1, LaBr2, and TAC L1-L2. This TAC starts when a gamma is detected in LaBr1 and stops when it is detected in LaBr2. By making a projection of this coincidence into the TAC, we can see peaks that have a slower decay on the right. This peak can be fit with an gaussian convoluted with an exponential decay. The half-life of the intermediate state can be measured by $log2/\lambda$ where λ is the exponential decay component of the convoluted gaussian. For this data, we have found the half-life of Tl_{183} to be 183.777 ps and Tl_{185} to be 158.948.

4. Conclusions

For completeness, the analysis of this project needs to be run several more times to develop accurate errors of the measurements made. Slight changes to the fitting parameters of the energy peaks can cause changes to the ECC and mixing ratio. The amount by which these measurement change, as well as statistical error involved in computation, will give insight to the total error of the results above.
The next step of this project is to calculate the binding energy of the E1 and M2 gammas measured in these Thallium isotopes. With this infomration, we can begin to make inferences about the shape of the excited state, allowing us to understand how the isotopes behave at different energy levels.

5. Acknowledgements

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