Gamma Spectroscopy

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Introduction

The radiation emitted by the nucleus of a radioactive source can be attributed to the angular momentum and the parity. Therefore the solutions to the wave equation are eigenfunctions of the angular momentum. These solutions are called ‘multipole fields’ and are classified by the amount of angular momentum imparted to the photon as the nucleus is de-excited. The multipole order is determined by *L*, the angular momentum, (*L*=1 dipole, *L*=2 quadrupole, etc). Energy imparted to the light quanta that are emitted is due to nuclear transitions of a linear combination of different L’s with the smallest order dominating. We have radiation created by both oscillating charge distributions (electric multipole) and oscillating currents (magnetic multipole) but the angular distributions of both types of radiation are equal.

Using Maxwell’s equations for the vacuum generated by a quadrupole and representing our angular momentum projection with the axis of the magnetic field as *m*, we can derive the electromagnetic fields as a combination of the Bessel functions for the radial directions and the spherical harmonics for the angular distribution.

$$\vec{E}_l^m \sim X_l^m \cdot j_L(kr);\ X_l^m = \frac{1}{\sqrt{l(l+1)}}\vec{L}\cdot Y_{Lm}(\theta,\phi);\ \vec{L} = -i(\vec{r}\times\nabla)$$

$$und\ \vec{B}_l^m \sim -\frac{i}{kc}rot(\vec{E}_l^m)$$

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There are certain transition rules that must be obeyed in any emission process based on quantum mechanical theory. Firstly the vector sum of the initial (I_1) and final states (I_2) of the nucleus angular momentum and the angular momentum of the radiation must remain constant. Also the absolute value of the change in *m* must be less than *L*.

$$|I_1 - I_2| \leq L \leq I_1 + I_2\ ;\ m = m_1 - m_2\ mit\ |m| \leq L$$

The parity also plays an important role in our experiment. The electric multipole radiation has the parity $(-1)^L$, likewise for the magnetic multipole $(-1)^{L+1}$. Non electric and magnetic multipole radiation is generated when the following parity rule is followed for the initial π_1 and final (π_2) parity states.

$$\pi_1 = (-1)^L \cdot \pi_2$$

Parity rules shape whether the electric multipole dominates the emission of radiation or whether the magnetic multipole contribute as well. Electric multipole radiation generally dominates the magnetic multipole radiation of the same order. The same is true for electric multipole radiation of order $L+1$ and magnetic multipole radiation of order L. If the parity does not change during a transition then the magnetic multipole radiation will contribute more significantly but it will have a smaller value of L so we can assume the electric multipole radiation contributes more and this is what we are measuring in the experiment. Information about the core structure of the nucleus depends on the multipole ratios and the spatial dependence of the radiation depends in turn on the multipole ratios, therefore, when we measure the spatial dependence of the radiation we can learn about the core structure. Knowing the details of the core structure allows us to learn such properties as the nuclear spin and paramagnetic charge of the nucleus.

The emitted radiation intensity is found from the pointing vector, which the cross product of the electric (E) and magnetic (B) field vectors of our above equations.

This experiment focuses on the gamma cascades and analyzes two of them more closely. The resulting energy spectrum is then analyzed for three different angles between two detectors and the angle-correlation is determined.

There are three dominant types of scattering occuring in the medium (air at room temperature) in front of the detector and in the detector itself. The photoelectric effect, Compton scattering and pair-production all interact with outer shell electrons of the medium where the gamma-radiation is absorbed or interacts with. Before the gamma photons are absorbed the germanium detector they sometimes interact with outer shell electrons in the air or in the detector and secondary electrons are generated that can in turn create a current that appears in our photon-peak spectra. These processes can basically be considered as noise and are not pertinent for us. (see fig. 1)

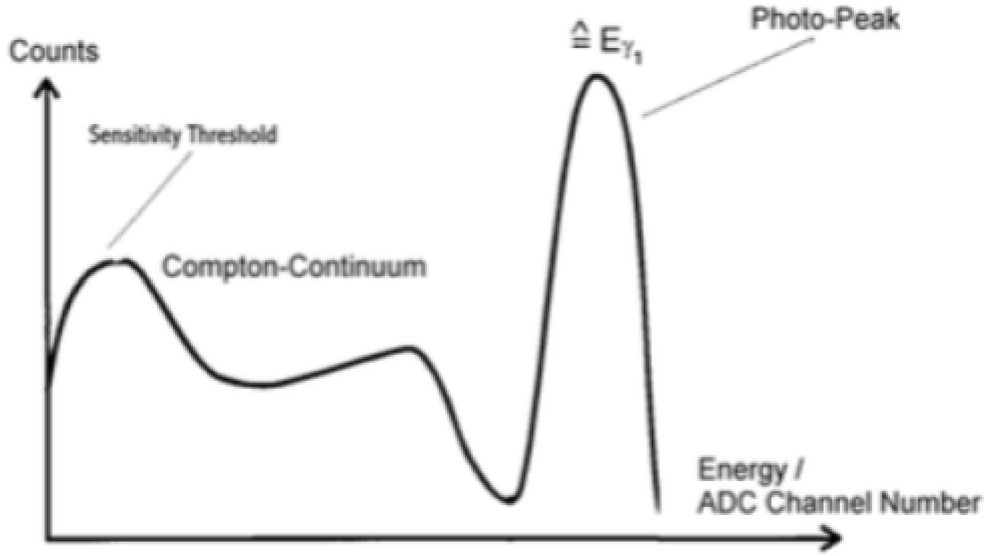

Fig. 1: An example of the photopeak spectrum vs. energy channel for the experiment.

Experimental Procedure

In order to investigate the cascades from an Europium-152 (Eu) source, where each cascade is a unique de-excitation series of different probabilities, measurements are performed at different angles with two Germanium (Ge) semiconductor detectors. The Germanium (Ge) semiconductor are chosen for their adequate resolution and insignificant deadtime in this set-up. In order to avoid thermal excitation, the semiconductors are continuously cooled by liquid nitrogen. The semiconductor is essentially a p-n diode. Each photon generates a free electron-hole pair by raising the electron from the valence band to the conduction band if the energy of the incident photon exceeds 2.9 eV (at 77K[1]) where the bandgap energy of Ge is 0.67 (at 0K) and the remainder of the energy is passed on to the excitation of phonons. The electrons and holes are separated and accelerated away from each other, '*the photo-voltaic effect*', by the internal electric field from the already separated charges with a depletion zone in between preventing diffusion and charge recombination. This depletion zone is extended by an applied reverse voltage. The low energy required to form an electron-hole pair results in a more complete collection of all the generated charge carriers and is therefore responsible for the high resolution of the Ge detector compared to scintillation detectors, where the resolution is defined as the Full Width Half-Maximum (FWHM). An external high voltage is applied to extract the electrons and generate a current for measurement. The current created in the detector is very small and is therefore amplified by an integrated circuit that consists of

[1] C. Hinke, L. Fabbietti, *Gamma Spektroskopie*, Lehrstuhl E12, Physik Department, TU-München 15. April 2007

a RC (resistor and capacitor) that is discharged over a transistor with filters (Hi- and Low-pass).

The collected charge at each detector is converted into a voltage signal with a pre-amplifier and an amplifier where the height of the signal pulse is proportional to the charge accumulation. The pre-amplifier is mounted directly on the detector to minimize the influences from eventual cables and environment. If two gamma photons are incident within a very short time frame then their signals overlap, pile-up events, and the sum of their energies are measured.

An event is only registered if there are two signals, one from each detector, occuring within a certain time interval or coincidence window. This is determined with a logical based on how high the signal is in the time-branch of the electronics with a limit of 5V in the trigger module. If the signal is high enough it activates the coincidence module in which two incoming signals amplitude, one from each detector, are superimposed with an AND-gate. If the signals are close enough in time, their superposition yields a higher potential which is registered as a true signal if it is higher than a preset threshold. If the signals are registered as coincidence the signal triggers the data acquisition in the energy branch of the electronics, via analog-to-digital-converter (ADC) which digitize the maximum value of the potential, where the potential is proportional to the incident energy of the gamma photons. The time difference between the two detector signals is also measured by a Time-to-Amplitude-converter (TAC) and the pulse height is proportional to the time difference and is digitized by an ADC independent on which detector registers a signal first.

Measurements were performed for three different angles; 180°, 135° and 90°, see fig.2. The histograms of collected data were then analyzed with the programm ‘ROOT’ where Gaussian-fits were performed on the histograms in order to evaluate the integrated number of counts, the standard deviation (σ), and the mean of each significant peak whilst ignoring the peaks from various scattering processes (mostly Photoelectric effect and Compton scattering). One count corresponds to a coincidence event. From these Gaussian-fits the *resolution* and *efficiency* can be estimated. The resolution is determined by the FWHM for Gaussian function; $\Delta E = \sigma \cdot 2 \cdot \sqrt{2 \cdot ln(2)}$ (se fig. 3). Whilst the Efficiency is evaluated by (se fig. 4):

$$E_{rel}(E) = \frac{number\ of\ detected(E)}{number\ of\ emitted(E)} = \frac{contents(E) \div W(E)}{content(1408\ keV) \div W(1408\ keV)} = \frac{content(E)}{content(1408\ keV) \div W_{rel}(E)}$$

Lastly, the two unique cascade coincidences 1408-122 keV and 1906-122 keV are evaluated to determine the sign of the parity of the radiation. For this there are a few parameters which are required and also necessary to evaluate such as the number of counts without the background:

$$N_C = N_A - N_R \cdot bins\,,$$

where N_A is the sum of counts in the peak and N_R is the background average per bin.
The rate $R = \frac{N_C}{t_r}$, where t_r is the run-time which needs to be corrected with the total counts without coincidence, normed with the total counts at 180° see table 2. Finally the corrected rate can be evaluated against measurement angle, see fig.5.

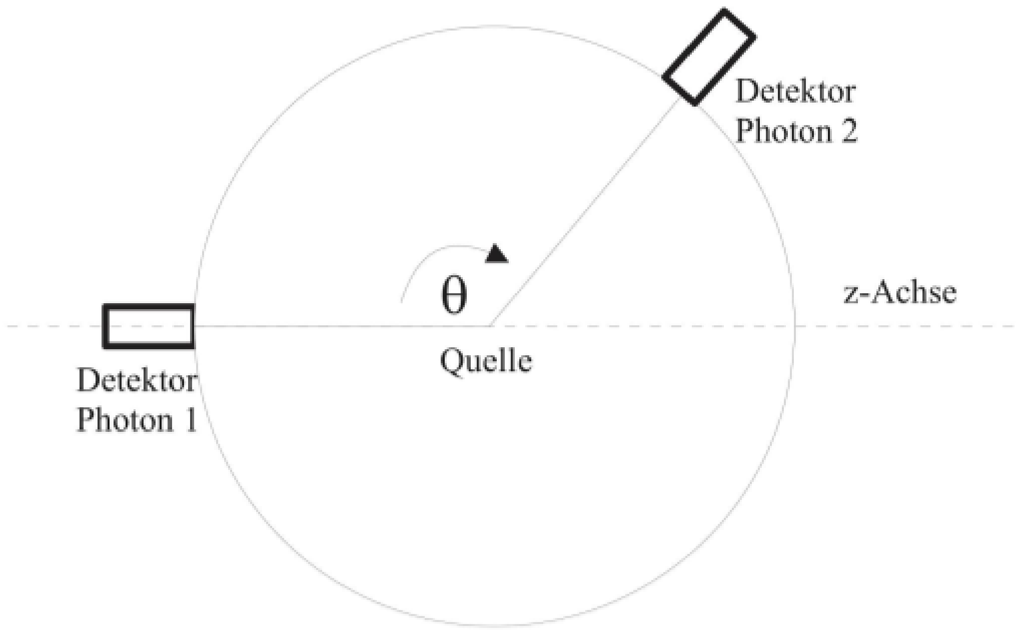

Fig. 2: Shows the relative positions of the detectors. The second one was placed at 180°, 135°, and 90° relative to the first one. The europium source is at the center of the circle.

Results

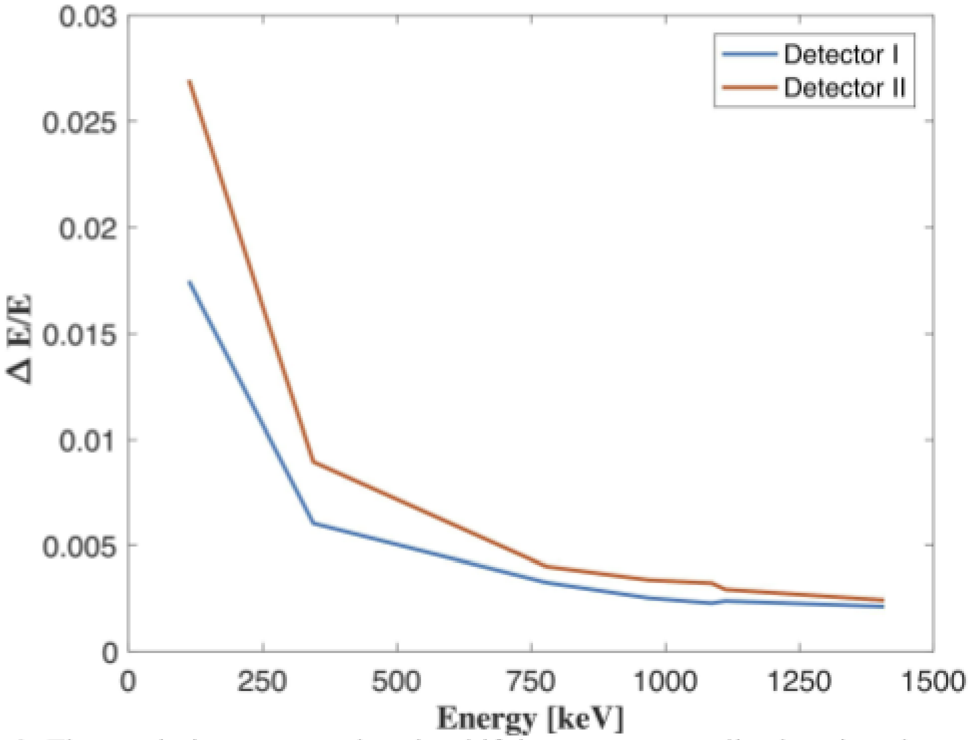

Fig. 3: The resolution expressed as the shift in energy normalized against the measured energy. The FWHM for a Gaussian function is ΔE = *std*2*sqrt(2 ln 2),* where std is the standard deviation. Detector I is static and Detector II is subtended 180 degrees from Detector I.

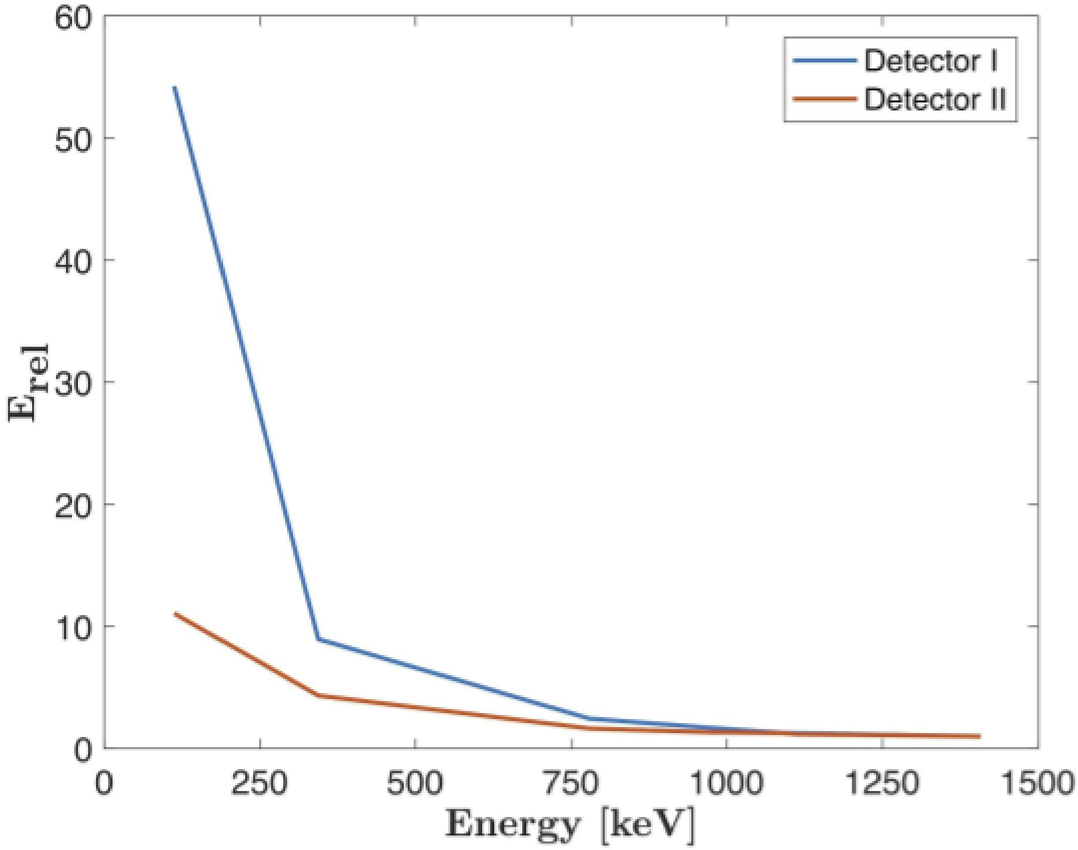

Fig. 4: The Efficiency of the detectors versus energy. Detector I is static and Detector II is subtended 180 degrees from Detector I.

Tabel 1: Estimation of the cascades which occurs yielded from the fraction of the number of counts against the background. Neither the 1086-122 keV nor the 1086-344 keV occurs since from this energy level the de-excitation occurs directly to the ground state.

Energy [keV]	122 [keV]	344 [keV]
779	F	T
964	T	F
1086	F	F
1112	T	F
1408	T	F

Table 2: The various parameters required in order to correct and normalize the count rate. The *Runtime* is the time for which each measurement were performed. *N_C* is the number of coincidence counts. The *Rate* is the uncorrected rate per second. *N_theta* is the number of counts in a 10 second period. The final *Rate_corrected* is the Rate normed over the weight of the *N_theta*.

	1408 - 122 [keV]			**966 - 122 [keV]**		
Angle [deg]	180	135	90	180	135	90
Runtime [s]	3909	7705	12711	3909	7705	12711
N_C	595	1059	1566	647	1164	2166
Rate	0.1522	0.1374	0.1232	0.1655	0.1511	0.1704
N_θ	28350	28065	29596	28350	28065	29596
N_θ/N_{180}	1	0.9899	1.0440	1	0.9899	1.0440
$Rate_{corrected}$	0.1522	0.1388	0.1178	0.1655	0.1526	0.1638

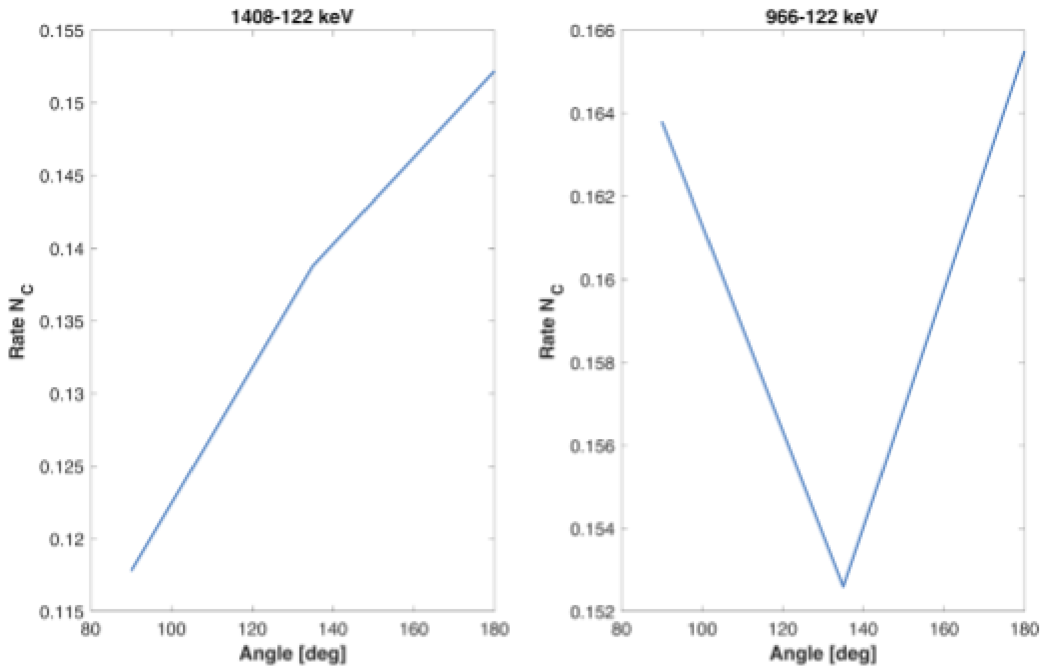

Fig. 5: The corrected count rate, adjusted from background counts, versus the angle of Detector II. Two cascades 1408-122 keV (to the left) and 966-122 keV (to the right). The parity of the levels from angular correlation can be yielded from the shape of the curve for both cascades.

Discussion and Conclusion

According to the collected data, the efficiency of detection is highest for the lower energies and the resolution is highest for the higher energies (lower values equals higher resolution, that is, the resolved distance is smaller), this corresponds to the experimental expectations of the detector. Improvements to detection efficiency can be acquired by the usage of multiple detectors instead of two. The resolution is dependent on impurities of the semiconductor, these can be reduced by either doping the Ge with lithium (Li) or using the more costly high purity Ge (HPGe).

For increased efficiency at higher energies, larger detector sizes are generally required. Also, at higher energies the NaI(Tl)-scintillator is more efficient however the energy resolution is much poorer. The Ge detector is highly dependent of the cooling, which makes the setup sensitive to errors in the cooling system and also requires more space.

In this experiment there is one positive and one negative parity. The 1408-122 keV cascade has a positive parity, therefore an even L and the 966-122 keV cascade has a negative parity, therefore an odd L. The sign of the parity relates to the change in orbital quantum number L (also angular quantum number) from one energy sub-level to the other.

The precision in the angles is unknown since the selection was based on markings on the floor. By including more angles of detection (although this will greatly increase the measurement time).