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PHYS480L

Photon Angular Dependence in β^+ Decay of ^{22}Na and ^{60}Co

Abstract:

The objective of this experiment is to predict and measure the angular dependencies of photons resulting from β^+ decay in ^{22}Na and ^{60}Co sources. Time coincidence techniques were employed using fast electronics to measure coincident photons for both elements, confirming theoretical expectations regarding the angular distribution of each primary decay chain.

Backround:

Radioactive materials emit particles as they decay to lower, more stable energy states. These emissions can be detected using fast electronics, possessing applications ranging from particle physics to medical imaging. One such example is Positron Emission Tomography, or PET, a routine procedure used to image tissue dynamically. This technology relies on a concept known as *β-decay*.

When a radionuclide decays to a lower energy state, it may do so with a high probability of releasing one or more charged particles. In *β-decay*, either an electron or its antiparticle (positron) is emitted in an effort to rebalance the internal charge structure of the atom so as to produce a more stable and therefore preferable configuration.

In this experiment, the β-decay of Na^{22} and Co^{60} isotopes was observed. The decay scheme of the former is given to the left in the figure below, and the latter to the right:

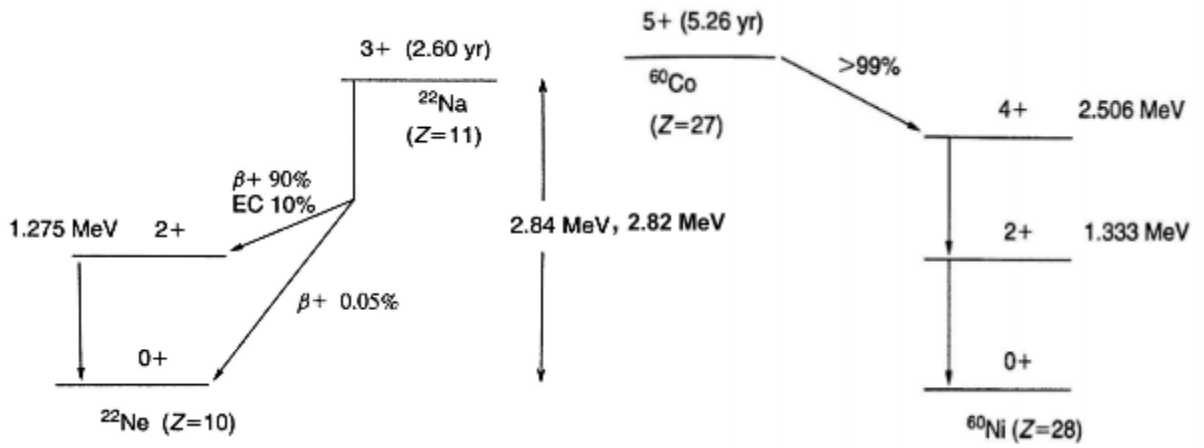

Figure 1: Decay schemes of ^{22}Na (left) and ^{60}Co (right). [1]

The ^{22}Na decay chain with the highest probability (>90%) is described by the pathway $^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$, in which e^{+} represents a positron. Due to the positive charge emitted this type of decay is referred to as β^{+} (beta plus) decay. In the presence of a surrounding medium such as the atmosphere, a β^{+} positron annihilates with an ambient electron according to $e^{+} + e^{-} \rightarrow \gamma + \gamma$.

Described pictorially,

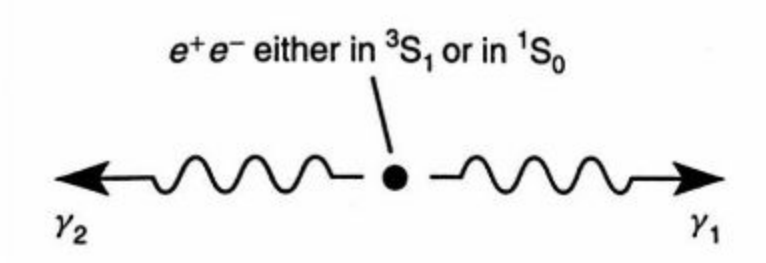

Figure 2: Two photon emission as a result of electron-positron annihilation. [1]

By conservation of momentum the gamma rays are emitted in antiparallel directions along the line of collision. It follows that the angular distribution function $C(\theta)$ describing the orientation of the two photons is given by a Kronecker delta centered on π radians. Mathematically,

$C(\theta) = \delta(\theta - \pi)$. It is assumed the line of each emission is uniformly distributed across all possible solid angles.

Apparatus:

Equidistant, antiparallel detectors were used to observe the annihilation events described above. The experimental apparatus consisted of two NaI(Tl) scintillation crystal detectors attached to photomultiplier tubes and a logic circuit, itself composed of discriminators, a delay box, coincidence unit, and scaler (counter), the block diagram of which is given below:

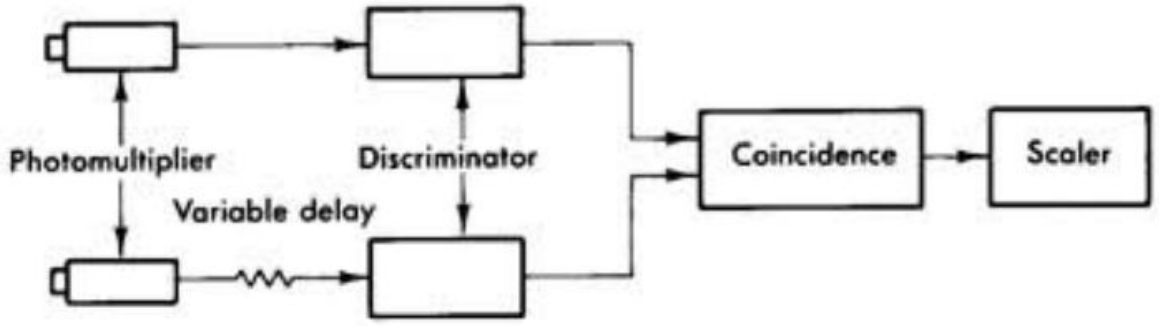

Figure 3: Block diagram of experimental circuit. Arrows indicate direction of signal propagation. *[1]*

The essential mechanism of the circuit is as follows:

1. A single photon is observed along the detector face and subsequently multiplied.
2. After some delay, the discriminator passes the signal from the photomultiplier only if it has reached the threshold voltage.
3. The signal from the discriminator and its twin enter the coincidence unit and are passed only if they arrive in tandem according to the specified temporal threshold.
4. The scaler reads the passed signal, and increments the successful coincidence count.
5. The cycle is repeated.

Procedure:

The source was placed an equal distance between the two detectors with one detector held stationary as the other was rotated incrementally, sweeping through an angle of 90° and pictured at a single point in time below.

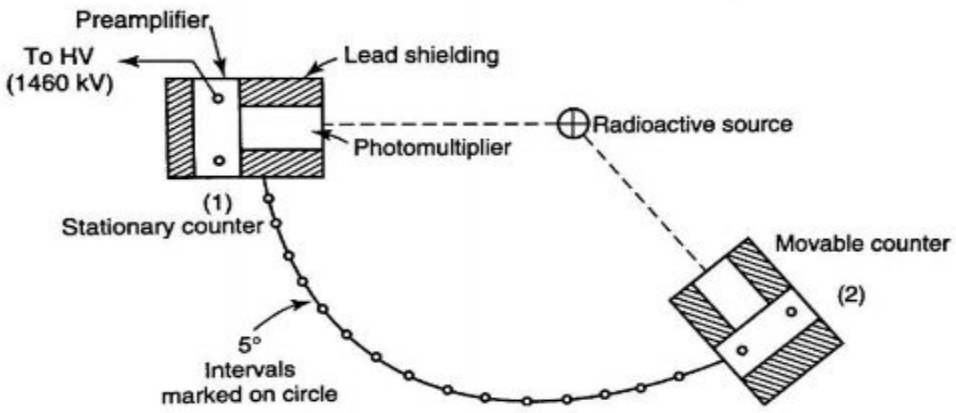

Figure 4: Experimental apparatus undergoing rotation. [1]

The distance from each detector to the source was held constant throughout each measurement set. A total of three distinct angular distribution measurements of ^{22}Na and one angular distribution measurement of ^{60}Co were taken in this way.

Calculations:

The equation used to fit the ^{22}Na data was a Gaussian with a constant offset of the form: $f_1(\theta) = \frac{d}{\sigma\sqrt{2\pi}} exp[-(\theta - \theta_0)/(2\sigma^2)] + c$, in which an implicitly random angular emission is presumed.

The equation used to fit the ^{60}Co data was a cosine with an integer offset of the form: $f_2(\theta) = 1 + a \cdot cos^2(\theta)$, in which the constant $a = \frac{1}{8}$ is a result of nuclear physics estimations.

The equation used to describe the overlapping area of the detector faces is of the form:

$f_3(\varphi) = 2R^2[cos^{-1}(|\varphi|) - |\varphi|\sqrt{1-\varphi^2}]$, where $\varphi = \frac{L \cdot sin(\theta)}{4R}$ is introduced for convenience and where L, R, θ are: the initial distance between antiparallel detector faces, the radius of each detector face, and the angular separation of the detectors, respectively. The resolving time of the circuit was estimated from the width of a delay curve representing the coincidence counts from the ^{22}Na source. The actual resolving time of the circuit was determined from the full-width at half maximum of f_3 for each distance configuration by using the FindRoot function in Mathematica.

Data:

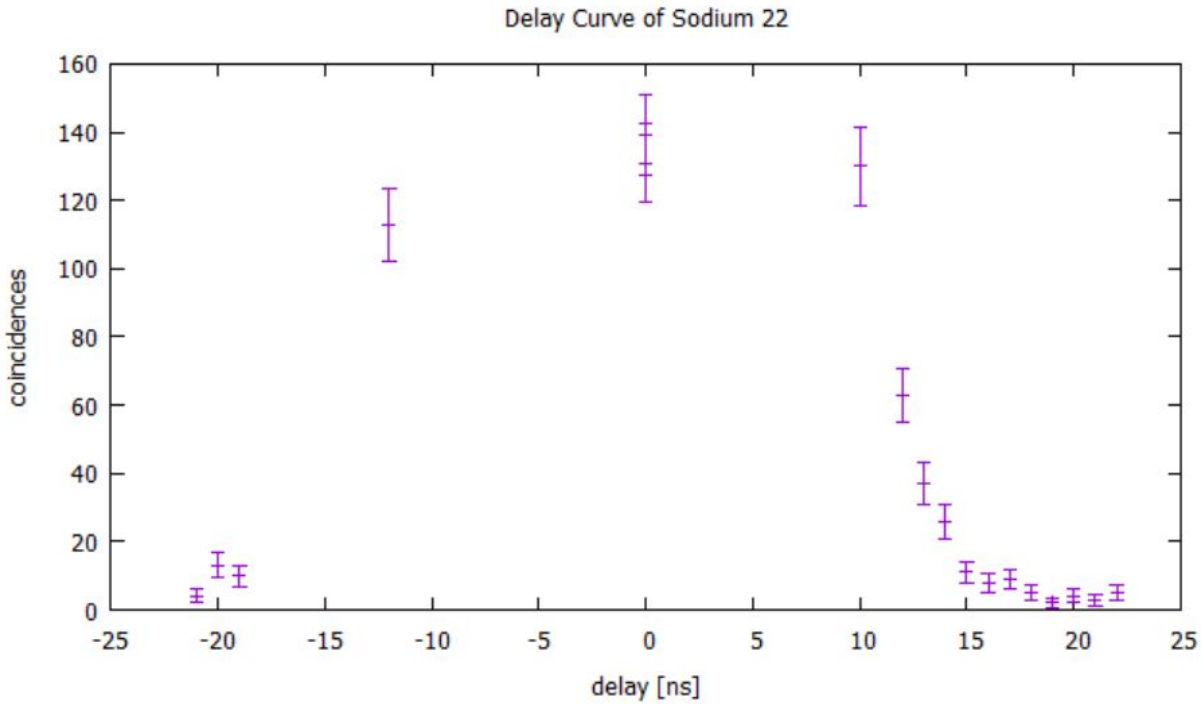

Figure 5: ^{22}Na delay curve representing temporal separation permitted by coincidence unit.

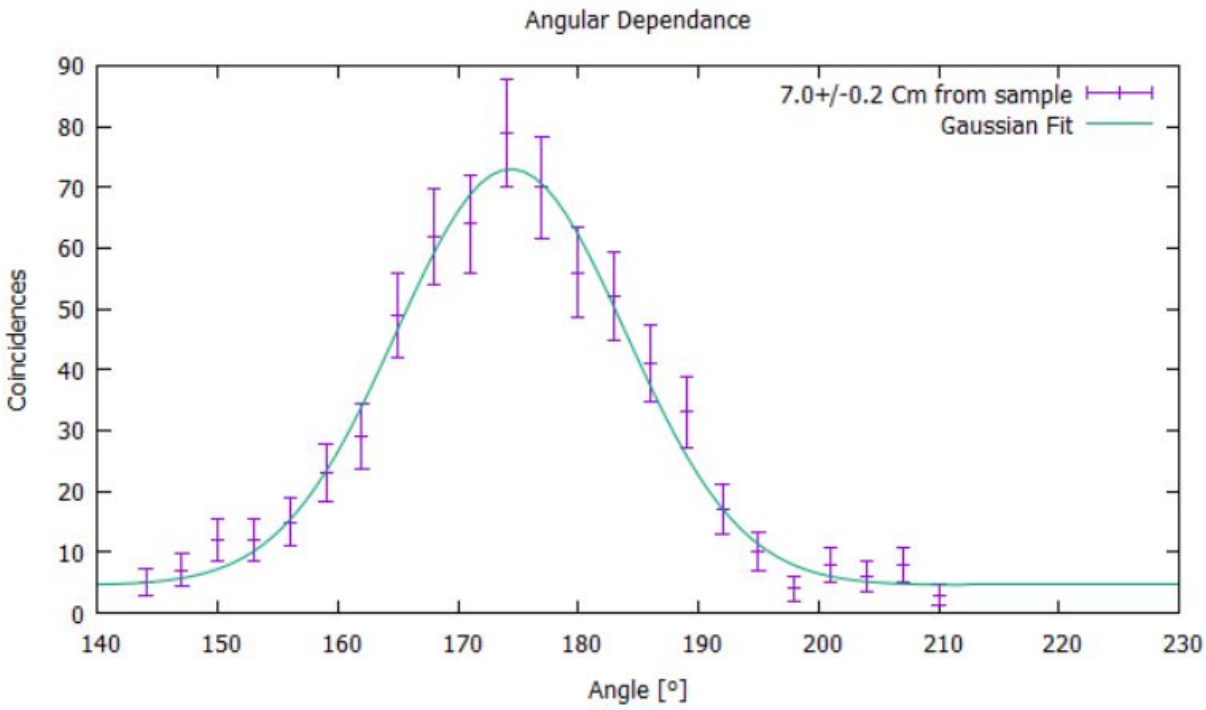

Figure 6: Angular distribution of ^{22}Na emissions with initial detector face separation L=(14.0+/-0.04) cm and FWHM=0.477 rad.

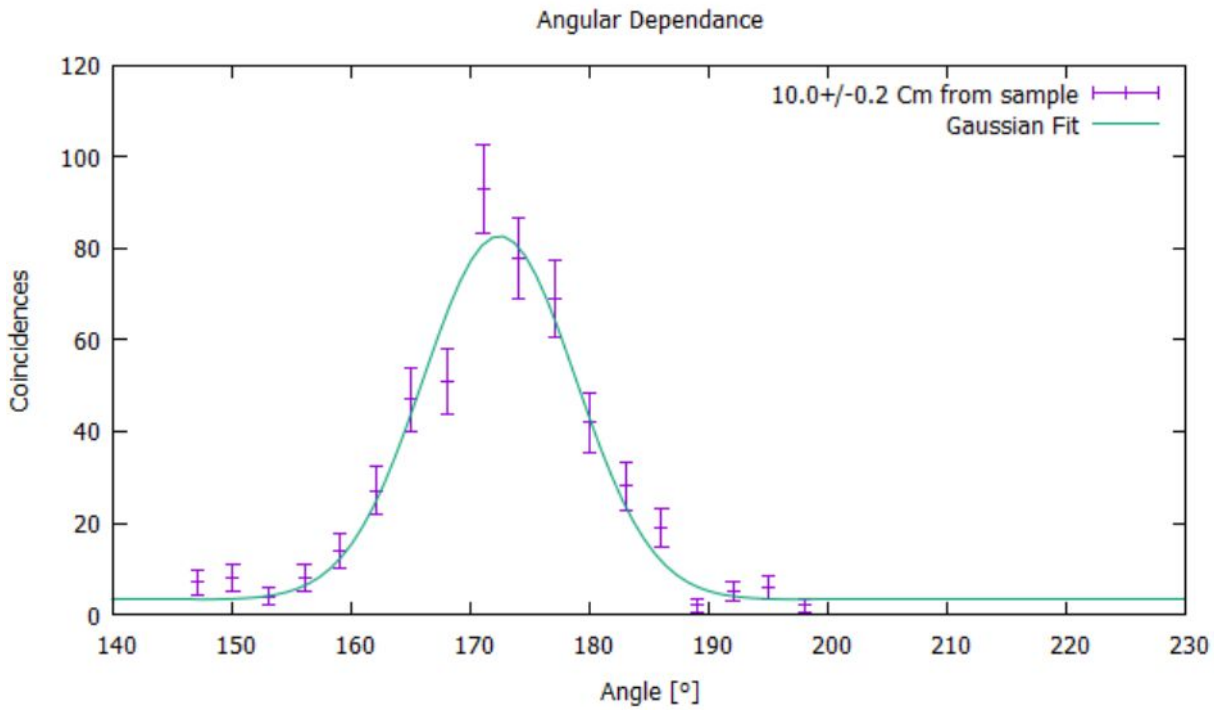

Figure 7: Angular distribution of ^{22}Na emissions with initial detector face separation L=(20.0+/-0.04) cm and FWHM=0.333 rad.

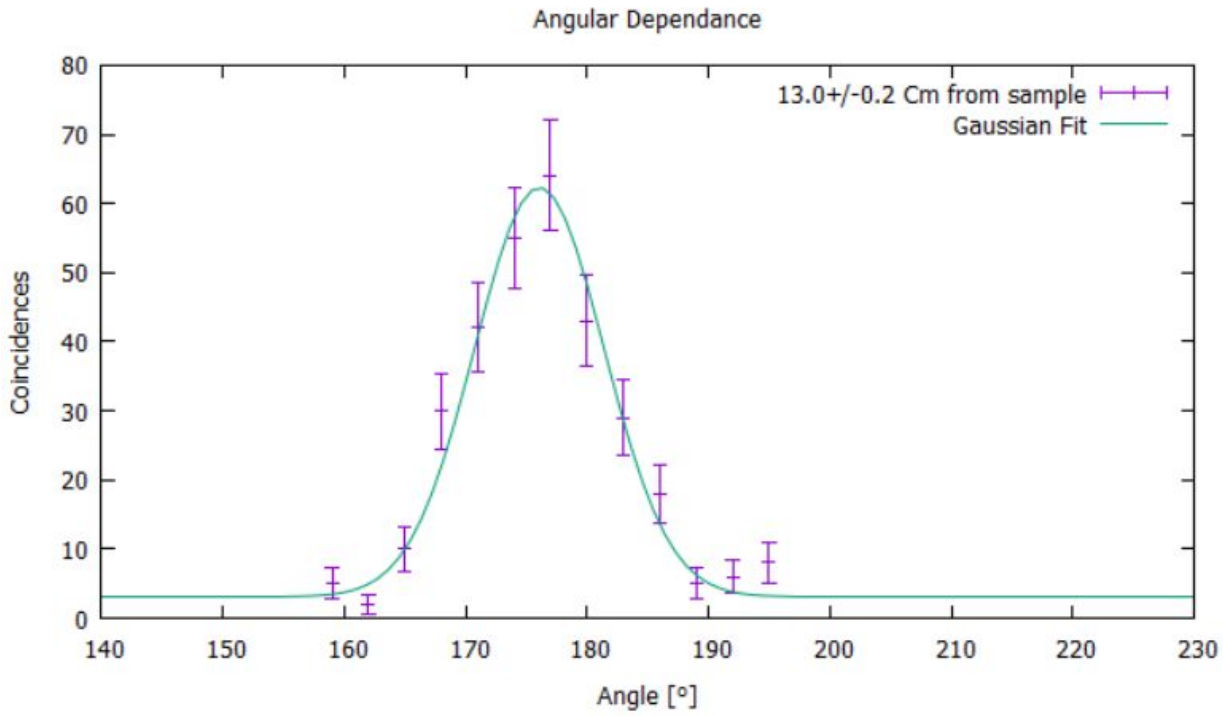

Figure 8: Angular distribution of ^{22}Na emissions with initial detector face separation L=(26.0+/-0.04) cm and FWHM=0.256 rad.

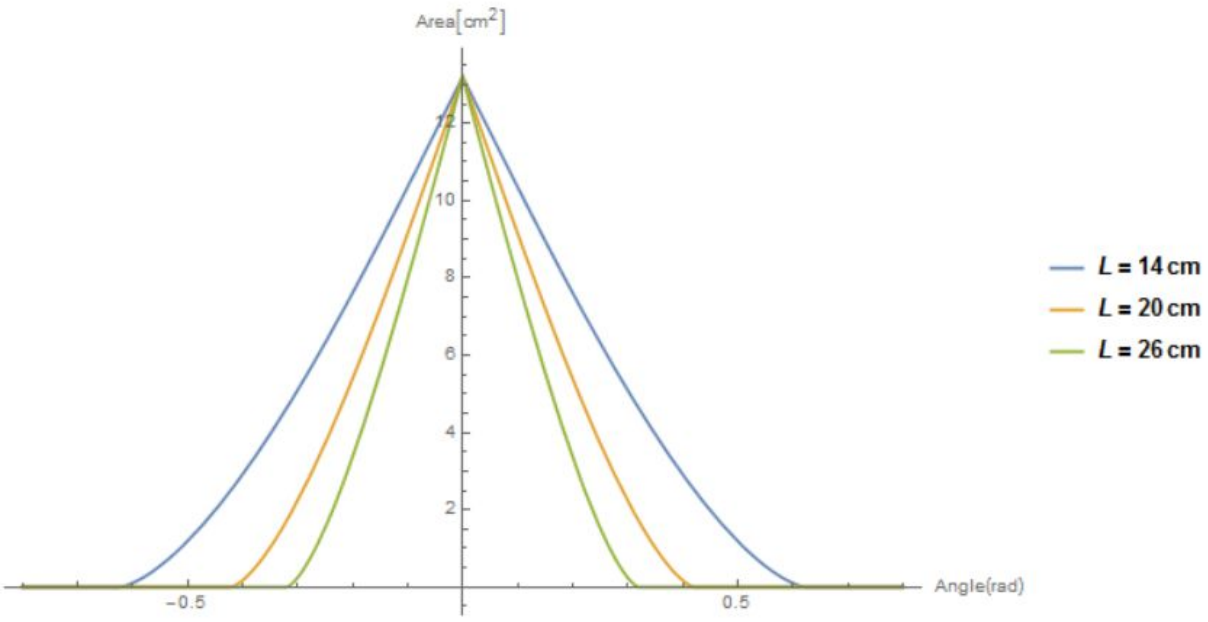

Figure 9: Overlap of detector faces as a function of linear and angular separation for all three ^{22}Na trails. Each curve represents a different linear separation corresponding to the three cases above.

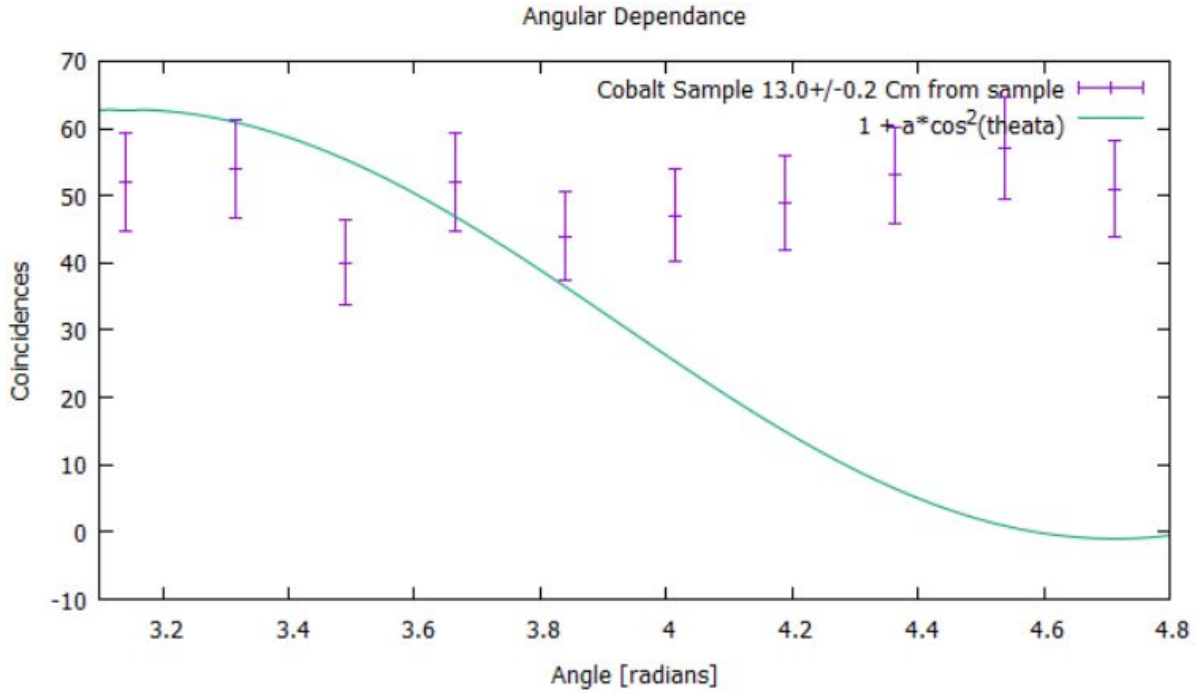

Figure 10: Angular distribution of ^{60}Co emissions with initial detector face separation L=26cm.

Discussion:

A strong correspondence between theory and measurement can be seen from the shape of the distributions given by Figures 6 through 8. The slight offset in the peak value in each case can most likely be understood as a result of the error in each measurement: 3° increments were used, and the observed offset in each case is of this order. The error itself was measured according to a Poisson distribution, in which the magnitude of the standard deviation is given by the square root of the number of measurements - mathematically, $\delta f = \sqrt{N}$ where δf is the error of the function f having N measurements.

The predicted ^{60}Co distribution did not match the observed data to within the appropriate amplitude of oscillation. However, it can be seen that the distribution does not increase or decrease monotonically, and varies over an approximately constant period. In this regard the

hypothesized cosine variational term is vindicated, but the actual fit is not. This is likely due to an error in the software and its implementation rather than the actual measurement process itself.

Conclusion:

Angular dependencies of gamma ray emissions resulting from ^{22}Na and ^{60}Co electron-positron annihilation were measured using fast electronics. The resulting distributions were fit to theoretical approximations and found to be in strong agreement in the case of ^{22}Na, and approximate agreement in the case of ^{60}Co.

References:

[1]: Melissinos, A. Experiments in Modern Physics, First Edition. New York Academic Press. Chapter 9. Accessed 9/26/2016.

Collaborators:

[1]: John Adamski,

[2]: Carly Hall,

[3]: Hendrik (last name to be determined)