

GAMMA DECAY LIFETIME AND ANGULAR CORRELATION

Part I

Nuclear γ decays occur on a tremendously fast time scale, typically a picosecond or less ($1 \text{ ps} = 10^{-12} \text{ s}$). Analogously to orbital electron decays, however, certain nuclear states are *metastable*, and thus can survive long enough for standard electronic techniques to be used. We will examine in particular the ^{57}Co decay chain, in which the two-step ^{57}Fe decay is exploited to allow a metastable lifetime measurement.

INTRODUCTION: GAMMA DECAY

The nucleus contains two different fermions: the proton and the neutron. Decays via α and β radiation change the population of both these particles, resulting in a new element via transmutation as described by Rutherford (Ernest Rutherford, New Zealand; 1871-1937; 1908 Chemistry Nobel). Nuclear γ decay, on the other hand, does not. Because the nuclear constituents (*nucleons*) are fermions, they develop a complicated energy-level structure analogous to the electron orbitals of atomic physics. Decay via γ radiation is simply the result of nuclear de-excitation analogous to the lower-energy photons emitted via electron orbital transitions.

Such transitions are quite likely immediately after α or β decay, which often leave the nucleus in an excited state. These decays can occur in multi-photon chains, but the typical ps time scale makes lifetime measurements difficult. If the first γ in the chain can be reliably identified, however, and the second is long-lived enough, one can measure the decay half-life with standard electronic techniques.

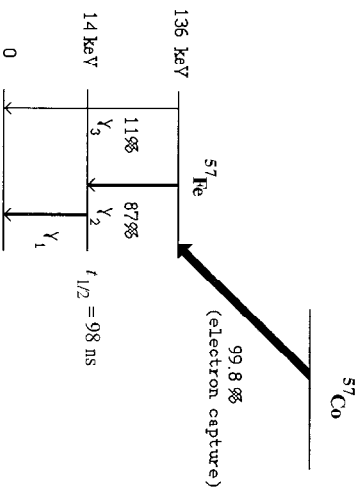


Figure 1: The $^{57}\text{Co} \rightarrow ^{57}\text{Fe}$ decay with subsequent gamma emission. Note that the contributions to not sum to 100% because some relaxations are nonradiative.

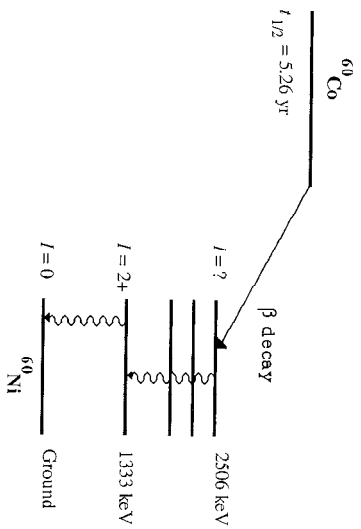


Figure 1: The ^{60}Co decay sequence.

In the nuclear shell model ^{60}Ni has four neutrons outside a closed ^{56}Ni shell of 28 neutrons and 28 protons. The nuclear spin I is due to these “valence” neutrons, and in turn determines the angular correlation function $W(\theta)$. This relates the 1.173 and 1.333 MeV gamma directions:

$$W(\theta) = \sum_{n=0}^2 A_{2n} P_{2n}(\cos \theta), \tag{1}$$

where θ is the angle between the gammas and the P_{2n} and A_{2n} terms are the Legendre polynomials and their relative contributions, respectively. Some possibilities are tabulated:

$$0^+ 6.2^+ 6.0^+ : \quad W(\theta) = \frac{5}{2} - \frac{15}{2} \cos^2 \theta + 10 \cos^4 \theta, \tag{2}$$

$$4^+ 6.2^+ 6.0^+ : \quad W(\theta) = 1 + \frac{1}{8} \cos^2 \theta + \frac{1}{24} \cos^4 \theta, \quad \text{and} \tag{3}$$

$$3^+ 6.2^+ 6.0^+ : \quad W(\theta) = \frac{11}{10} - \frac{9}{24} \cos^4 \theta. \tag{4}$$

THE CORRELATED GAMMA DECAY APPARATUS

Review photomultiplier and single channel analyzer operation from Part I. The PMT’s in this lab are both “standard” versions and run at approximately +1 kV. The preamp signals go to delay amplifiers, adjusted to get amplified unipolar positive outputs in the range of a few volts (Fig. 2), which in turn go to single channel analyzers and a coincidence unit.

photocathode lining, again undergoing the photoelectric effect. There are 10^4 or more such low-energy photoelectrons inside the PMT for each original high energy gamma ray in the scintillator, which are attracted by a strong electric field to the *dynode chain*, a series of positively charged plates near the base. They cascade down the dynode chain, giving a final charge magnification on the order of 10^7 or more, with output proportional to the original γ energy.

Both a "standard" and a *thin window* PMT are used here, the latter having a special thin covering on the front to allow better transmission of the low energy ^{57}Co 14 KeV gamma. Both operate at approximately +1 kV. Both photomultiplier signals are fed through delay amplifiers with unipolar, positive amplified pulses in the range of a few volts.

THE GAMMA DECAY LIFETIME EXPERIMENT

This laboratory includes the use of radioactive materials. Although not strong enough to warrant NRC licenses, they must be treated with care. As always, food and drink are prohibited from the laboratory. This experiment also uses high voltage power supplies. No connections to them should be made while at potential.

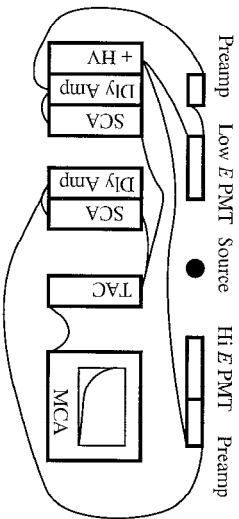


Figure 2: The nuclear lifetime apparatus.

Use the *single channel analyzers* to select a specific range of signal energies, in our case the 14 and 122 keV lines of Fig. 1. First feed the undelayed amplifier signal to the SCA, and turn the lower level discriminator all the way down and the window (ΔE) all the way up. Set the full window to 10 V and the mode to LE (that is, use the leading edge discriminator). Put the delayed amplifier signal and SCA output (positive) into the scope. Adjust the SCA delay until the gate rests under the peak of the amplified signal then remove the scope and feed the signal and gate to the multichannel analyzer (MCA). Isolate the relevant energy peak with the lower level and ΔE knobs.

Once the SCAs have been set, turn their delay back down to minimum and feed the negative output to the time analyzer (TAC). Set the full output range to something appropriate for the ≈ 100 ns lifetime of the intermediate state, and feed the TAC output into the MCA. Most likely only the first 1 k channels will be used (that is, set the ADC gain to 1024 and use the first 1/4 of the

memory). Use the high energy SCA output for the start and the low energy output for the stop. The TAC gate switch should be sent to *anti*, allowing all signals to be processed unless a gate signal is received. Since we don't gate the TAC, it will then run freely.

When properly configured the laboratory should produce a falling exponential decay curve on the multichannel analyzer. There will also be a constant background due to random coincidences from separate nuclei, cosmic rays and other background, *etc.* Transfer the MCA output to a computer and make a fit to the decay using an exponential (or half-life function) with constant background. Determine the lifetime of the state and compare to nominal. In addition measure the individual SCA signal rates and use these, along with the TAC coincidence window, to calculate the expected background and determine whether it is consistent with observation.

Goals

A complete laboratory report will

- Measure the ^{57}Fe gamma decay half-life, and
- Compare the background rate to expectation.

Part II

Beta decay results in the transmutation of a nucleus from one atomic number to another, with $\Delta Z = \pm 1$ depending upon whether e^- emission, e^+ emission, or electron capture occurs. Often, the new nucleus is not in the ground state but will eventually reach it via the emission of nuclear gamma rays. In those cases where multiple transitions (gammas) are involved, angular correlations among them are determined by the spin state. It is possible to use the ^{60}Co beta decay to ^{60}Ni and subsequent gamma emissions to examine this effect.

INTRODUCTION: GAMMA DECAY ANGULAR CORRELATIONS

Decay via γ radiation de-excites the nucleus in a process analogous to electron orbital transitions. As in atomic optics, the physics governing these decays can force a relationship between the properties of outgoing photons which originate in single decay cascade. As shown in Fig. 1, ^{60}Co decays via e^- emission to ^{60}Ni , which then emits two gammas on the way to the ground state. The lifetimes are less than a picosecond (1 ps = 10^{-12} s) so they appear simultaneous to our electronics, with nuclear spin information translated into the gamma-gamma angular correlation.

Examine the decay of ^{57}Co to ^{57}Fe via electron capture (Fig. 1). This leaves the new iron nucleus in an excited state, from which it can decay to ground either via a single $136\text{ keV } \gamma$ (1% of the time) or via a two-step 122 keV , 14 keV process. In the latter case the second transition is metastable and so has a lifetime long enough to observe with conventional electronics (at almost 100 ns it is quite long by nuclear standards).

In the nuclear shell model protons and neutrons pair up in the core of the nucleus, about which their unmatched counterparts orbit. The nuclear spin, then, is the angular momentum of these unpaired nucleons. In the ^{57}Fe ground state all twenty-six protons and thirty of the thirty-one neutrons are paired. The unpaired neutron is in a spin $3/2$ orbital (see Eisberg and Resnick, Ch. 15), so one would naively expect the ground-state spin to be $3/2$. In fact a slightly more complicated model is required, and the $I = 3/2$ level is actually excited by 14 keV above the ground-state $I = 1/2$ level.

Since the ground and 14 keV excited-state both have odd parity, electric dipole radiation is prohibited and the lowest-energy excited state is metastable. A *magnetic* dipole transition can connect states of the same parity, however, so the decay *will* eventually occur—it just takes longer. The strength of the magnetic interaction goes like $\beta = v/c$ as compared to the electric interaction, so magnetic transitions are proportionally suppressed even though nuclear velocities are high. The fact that the dipole transition rate scales as E^3 doesn't help either, since 14 keV is not much for a nuclear gamma. So the state lives long enough to be observed by standard timing electronics.

THE GAMMA DECAY LIFETIME APPARATUS

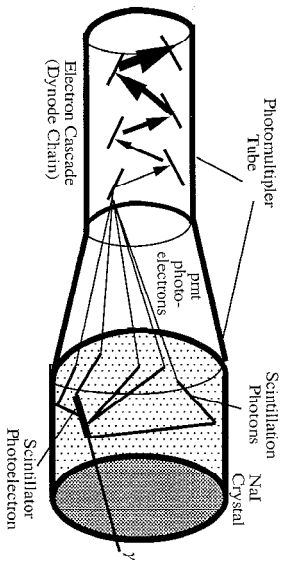


Figure 2: Sodium iodide (NaI) scintillator and photomultiplier tube.

This laboratory employs two scintillator/photomultiplier detectors (Fig. 2). When a γ strikes the scintillator sodium-iodide (NaI) scintillator crystal, it can give up all of its energy via the photoelectric effect (we ignore other interactions for now). The resulting high energy *photoelectron* ionizes sites along the lattice, and light is given off by the subsequent electron recombinations. A photomultiplier tube (PMT) detects this light when the recombination photons strike its

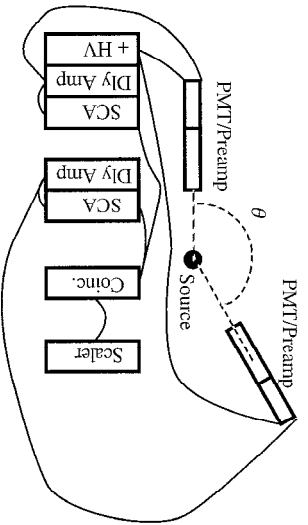


Figure 2: The nuclear decay apparatus.

THE CORRELATED GAMMA DECAY EXPERIMENT

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Review the Gamma Decay Lifetime part of this experiment for the procedure to isolate each of the decay gammas in Fig. 1. Scale the coincident data for at least ten different angles between 0 and π . Plot the results and make a fit to each of the three possibilities of Eqs. 2-4. Include a constant background term. Use the fits to determine the spin of the top-level excited ^{60}Ni state.

Goals

A complete laboratory report will

- Demonstrate the ^{60}Co decay gamma angular correlation,
- Determine the spin of the upper-level excited ^{60}Ni nucleus, and
- Compare the background rate to expectation.