

NEUTRON EXPERIMENTS

In 1932 James Chadwick bombarded beryllium with α particles. In order to completely explain the reaction involved, now known to be ${}^9\text{Be} + \alpha \rightarrow {}^{12}\text{C} + \text{n}$, he postulated the existence of a "new" neutral particle, which he named the **neutron**. It was for this work that he was awarded the Nobel Prize for Physics in 1935.

A free neutron has a rest mass of 939.573 MeV, compared to 938.280 MeV for the proton. It has zero charge, but a magnetic moment of $1.9135 \mu_N$ (μ_N is the nuclear magneton). This in itself indicates that the neutron is not an elementary particle but a composite. It is in fact composed of 2 d quarks and 1 u quark. It has a spin of 1/2, the same as the proton. Free neutrons undergo β decay to protons (half-life = 10.26 ± 0.04 minutes.), while neutrons bound in a nucleus apparently are stable.

This experiment is designed to familiarize you with interactions between neutrons and nuclei. The neutrons available are "fast", i.e., energetic neutrons with up to several MeV of kinetic energy. They are "moderated" by scattering off protons in water, to become "slow" neutrons with only a few eV of energy, and finally "thermalized" (average kinetic energy at room temperature $\sim kT \sim 0.025$ eV). Thermal neutrons are readily captured by nuclei in an (n,γ) reaction, changing the nucleus (Z,A) into $(Z,A+1)$ and leaving it in an excited state. For certain nuclei, notably B, Cd, and Gd, these thermal capture processes have enormous cross sections much larger than a barn. Even the capture cross section for H is large enough so that it becomes easy to absorb neutrons from any neutron source by shielding it with water, the material acting both as a moderator and a capture target. Slow, thermal, cold, and ultra-cold neutrons are widely used for non-destructive activation analysis of materials, and studies of condensed matter.

NEUTRON SOURCE AND DETECTOR

NEUTRON SOURCE:

A Californium source (${}^{252}\text{Cf}$) will be used here. ${}^{252}\text{Cf}$ decays by α decay and by spontaneous fission in the following manner:

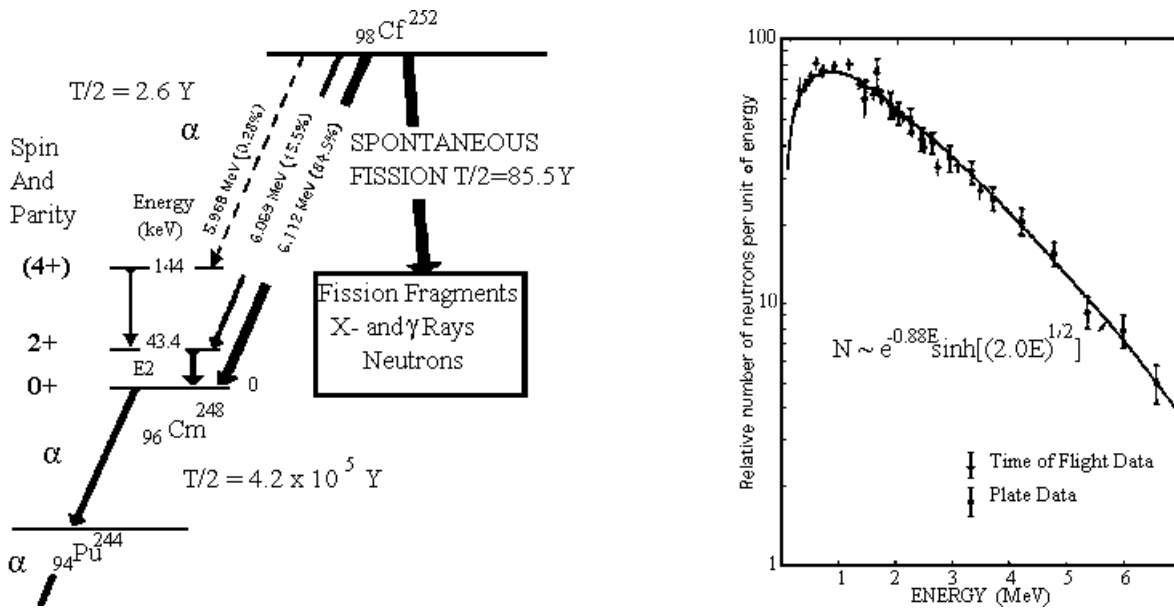
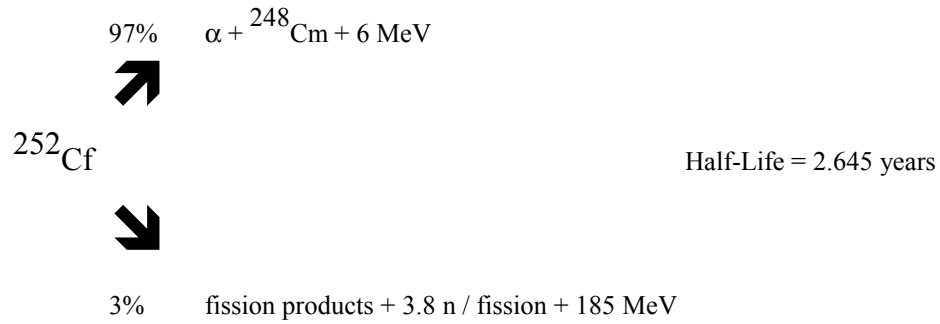


Figure 1. The ${}^{252}\text{Cf}$ decay scheme and energy spectrum of fission neutrons. The fission neutrons have a broad energy spectrum peaked at ~ 1.5 MeV, but extending up to 13 MeV. Also emitted are γ -rays (< 6 MeV) and X-rays from both fission products and ${}^{248}\text{Cm}$.

The ${}^{252}\text{Cf}$ neutron output is moderated by placing the source in a 350-gallon tank of ordinary water. The neutrons quickly lose energy by scattering off the H atoms in the water. For a point source of thermal neutrons in an infinite homogeneous medium (H_2O), an approximate solution of the diffusion equation for the flux ϕ at large r , is:

$$\phi = \frac{3S}{4\pi\lambda_{tr}} \frac{e^{-r/L}}{r}, \quad \text{where:}$$

$$L = \text{"diffusion length"} = \sqrt{\lambda_{tr}\lambda_a/3}$$

$$\lambda_{tr} = \text{"transport mean-free-path"} = 1/N_0\sigma_s(1 - 2/3A),$$

$$\lambda_a = \text{"absorption mean-free-path"} = 1/N_0\sigma_a,$$

A = atomic weight of scatterer ,

N_0 = number of hydrogen atoms ($A = 1$) per unit volume

(The oxygen content of H₂O can be ignored for both scattering and absorption.) ,

σ_s = scattering cross section per H atom ,

σ_a = absorption cross section per H atom , and

S = source strength.

A 2-MeV neutron requires, on average, only 25 collisions with protons to be slowed to the "thermal" range. See Figure 2.

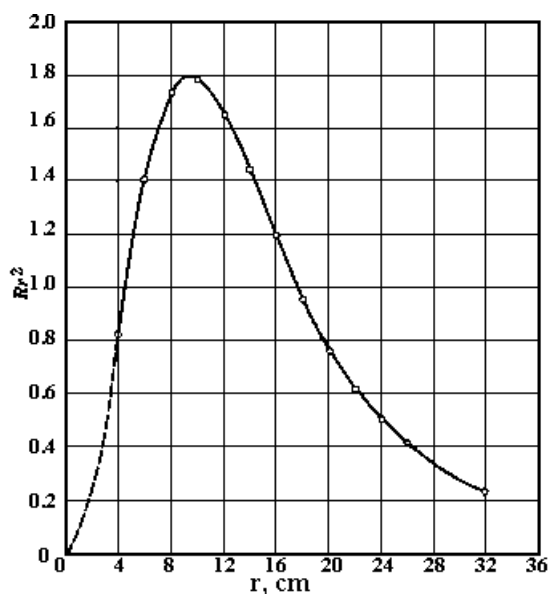


Figure 2. Radial distribution of thermal neutrons in water. NB: Neutrons of all energies make up the total flux seen at any point. R = neutrons/cm²sec, and r = radial distance from a point source.

This source contained 18.7 μg of ²⁵²Cf on **1 January, 1994**.

$$18.7 \mu\text{g} \times (2.4 \times 10^6 \text{ n/sec}/\mu\text{g}) = 4.5 \times 10^7 \text{ n/sec}$$

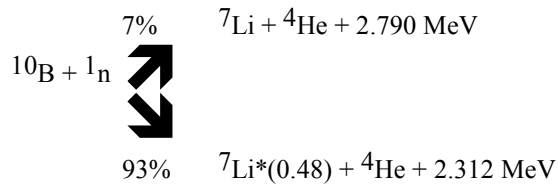
$$\times (0.537 \text{ mCi}/\mu\text{g}) = \mathbf{10.0 \text{ mCi}}$$

The doubly sealed source is always kept in the tank to insure the minimum of biological damage. **The measured neutron flux at the outer surface of the moderator tank is $\ll 1 \text{ min}^{-1}\text{cm}^{-2}$. (5 January 1994)**

NEUTRON DETECTOR:

The detector used for this experiment is a cylindrical proportional counter that contains an isotopically enriched ¹⁰B fill gas that responds to neutrons via the ¹⁰B(n, α) reaction. The counter is operated in the "proportional" region, producing output pulses that are accurately proportional to the energy that the charged particles, produced by the reaction process, deposit in the counter gas.

BF₃ DETECTOR CHARACTERISTICS: This BF₃ (Boron-triFluoride) Counter (TGM/Centric Model 12EB20/25 non-standard proportional counter with < 4% FWHM resolution) has a copper wall 2.54 cm outside diameter, total length of 23.5 cm and an active length of 10.5 cm between the Cd sleeves. The fill gas is BF₃, with a > 90% ¹⁰B enrichment, at a pressure of 20 cm Hg. Background counting rate due to internal α-particle contamination is <1 cpm. Naturally occurring boron exists in the proportion 19.9% ¹⁰B to 80.1% ¹¹B. The tube capacitance is 7 pf, and the operating bias voltage range is 1.3 - 1.6 kV. ¹⁰B has a capture cross section of 3840 barns for thermal neutrons. The reaction is



The Li and He reaction products share the energy released by the reactions as listed above.

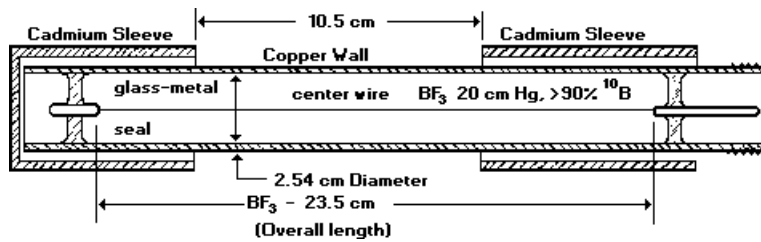


Figure 3. BF₃ proportional counter tube geometry.

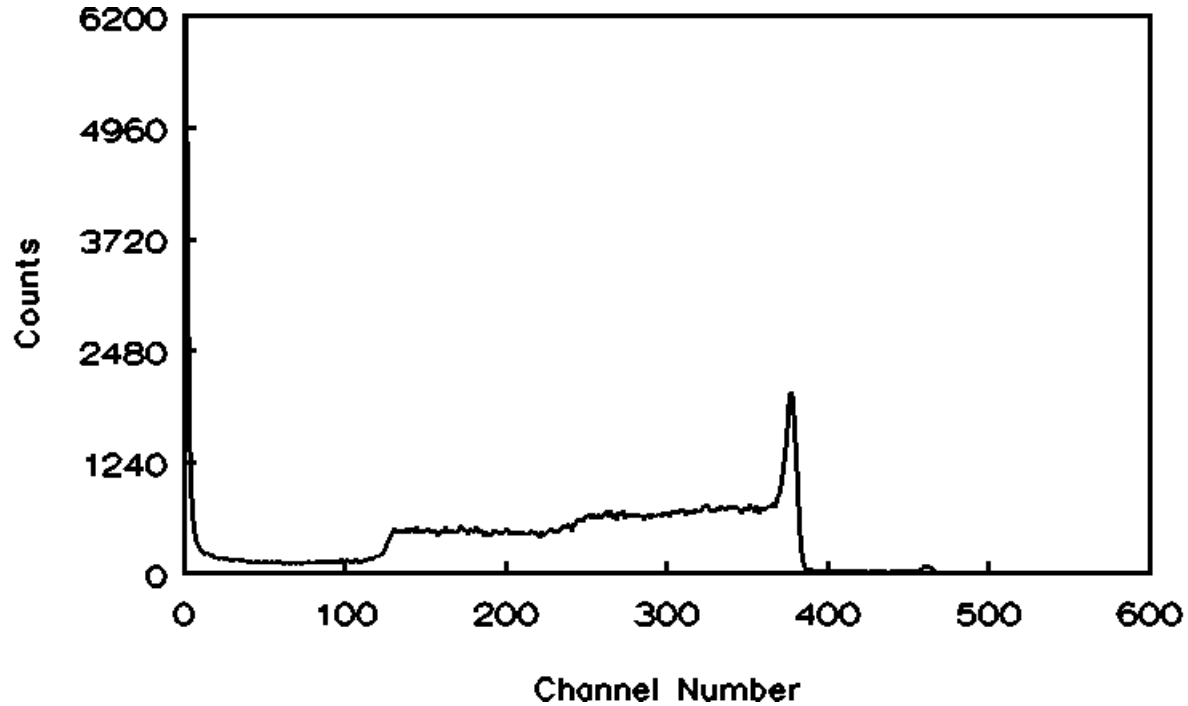
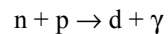


Figure 4. Pulse-height spectrum from the BF₃ Counter. The two plateaus are characteristic of wall effects in a small volume counter exposed to randomly incident neutron flux (Reference 1., p.524 - 528). The very low energy events are due to γ rays and electronic noise.

NEUTRON CAPTURE REACTIONS

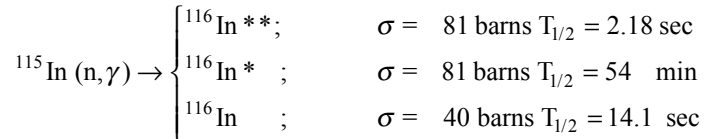
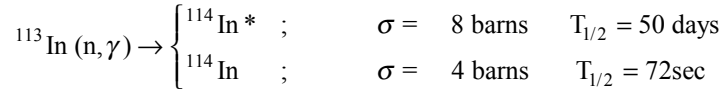
If the thermal neutrons are captured by hydrogen nuclei, they produce deuterium by the reaction:



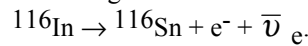
The binding energy of the deuteron is released in the form of a 2.223 - MeV γ ray. The strength of this γ ray (counts/sec) is thus a measure of the neutron flux.

ACTIVATION OF MATERIAL (INDIUM) BY SLOW NEUTRONS (n, γ):

Slow and thermal neutrons interact with indium to produce excited states. Natural-abundance indium has two stable isotopes, ¹¹³In (4.2%) and ¹¹⁵In (95.8%). The neutron-capture reactions are:



Data on capture cross sections are available in the Appendix. Because of the higher isotopic abundance of ${}^{115}\text{In}$, and its larger cross section, the predominant radioactive isotope formed is ${}^{116}\text{In}$ and isomeric states. ${}^{116}\text{In}$ and ${}^{116}\text{In}^*$ decay via β decay into stable ${}^{116}\text{Sn}$ according to:



While the decay from the ${}^{116}\text{In}$ ground state (1^+) proceeds directly into the ${}^{116}\text{Sn}$ ground state (0^+), the isomeric states decay into excited states of ${}^{116}\text{Sn}$. Several γ rays are emitted in their de-excitation.

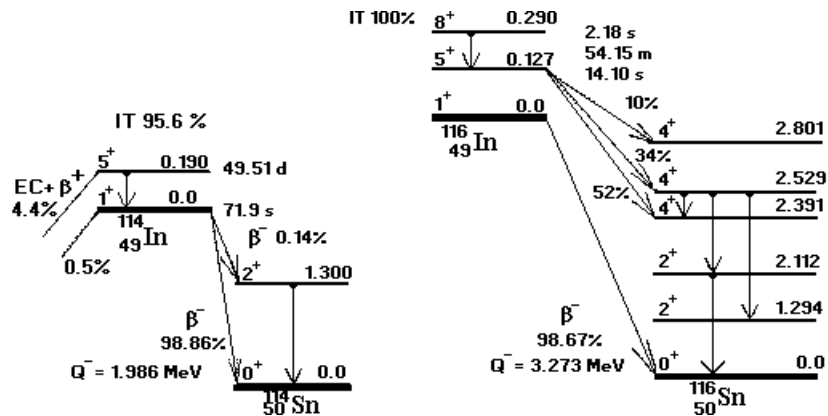


Figure 5. Simplified decay schemes for indium isotopes.

When a *very* thin sample is irradiated, the rate of activation is directly proportional to the neutron flux. *Thick* samples perturb the neutron flux and depress the rate of activation. While any sample is being activated, it is also decaying. Thus we have two competing processes that determine the absolute value of the radioactivity of the sample at any point in time. The rate of activation is given by:

$$R = \sigma\phi N_t \text{ (for thin samples),}$$

where ϕ = average neutron flux, σ = activation cross section, and N_t = number of target nuclei. The rate of decay is given by λN , where $\lambda = 1/\tau$ = the decay constant, and N = the total number of radioactive nuclei present. The rate of change in N is the difference between the rate of activation and the rate of decay:

$$dN/dt = R - \lambda N$$

A detailed discussion of the rates of activation and decay will be found in Reference (1), p. 765 - 771, and Reference (2) Chapter 19.

ELECTRONIC INSTRUMENTATION

BF₃ PROPORTIONAL COUNTER INSTRUMENTATION:

PREAMPLIFIER: A Canberra Model 2006 Charge-Sensitive preamplifier provides the interface between the counter tube and the main linear shaping amplifier. It is a charge-to-voltage converter followed by a voltage amplifier and a direct-coupled cable driver output stage with an output impedance of 93 Ω. The equivalent noise of the unit is about 380 ion-pairs RMS. Maximum linear output is ± 10 volts with a rise time of < 25 ns and a 50 μs falltime.

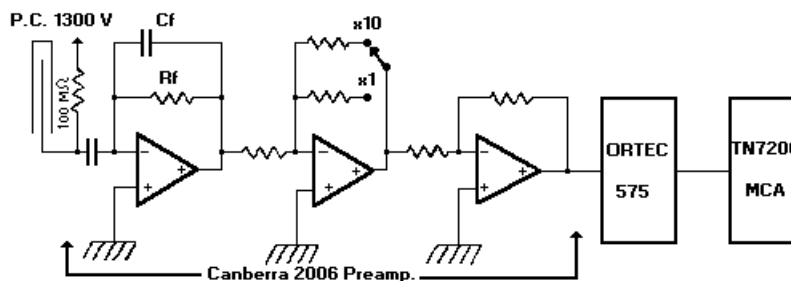


Figure 6. Block diagram of BF₃ Proportional Counter electronics.

LINEAR SHAPING AMPLIFIER: The Ortec Model 575 Linear amplifier provides a gain range of 5x to 750x, a semi-Gaussian pulse-shaping network, non-linearity of < 0.05% for outputs of ± 10 V, and less than 5 μV equivalent input noise. Gated active base-line stabilization with automatic threshold circuitry insures minimum broadening of spectrum features at count rates of < 50,000 c/s. Pulse-shaping time is set to 3 μs.

GeLi γ - RAY - DETECTOR INSTRUMENTATION:

PREAMPLIFIER: This is a FET input charge-to-voltage converter optimized for service with a low-leakage, low-capacity cooled germanium detector. It has an equivalent input noise of < 750 eV, an integral non-linearity of $< 0.05\%$, a maximum count rate of 150,000 c/s, and a maximum linear output of ± 9 V.

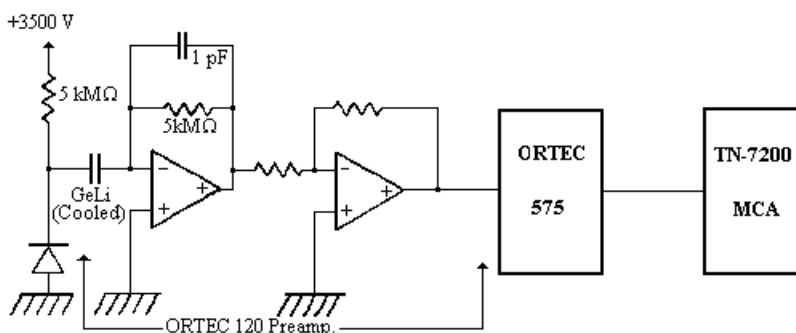


Figure 7. Block diagram of GeLi detector electronics.

LINEAR SHAPING AMPLIFIER: The Ortec Model 575 Linear amplifier provides a gain range of 5x to 750x, a semi-Gaussian pulse-shaping network, non-linearity of $< 0.05\%$ for outputs of ± 10 V, and less than $5 \mu\text{V}$ equivalent input noise. Gated active base-line stabilization with automatic threshold circuitry insures minimum broadening of spectrum features at count rates of $< 50,000$ c/s. Pulse-shaping time is set to $3 \mu\text{s}$. An active asymmetrical base-line restorer (BLR) provides dramatic improvement in the measured energy resolution of an "older" detector (such as the one here) that exhibits low-frequency noise.

EXPERIMENTAL TASKS

The suggested sequence is to plan to do Section (1) and Section (2), Part (A) the first session and Section (2), Part (B) the second session.

(1) STUDIES WITH THE BF_3 NEUTRON COUNTER:

(A) Place the detector in one of the stainless steel tubes that dip into the water of the moderator tank, with that tube about halfway out from the center ^{252}Cf source mounting column. (See Figure 9.) The optimum operating bias voltage for the counter is 1400 V. Be sure that the short length of RG-71B cable (Clear jacket with silver-plated braid) connects the detector to the Canberra Model 2002 preamplifier input. Handle the counter carefully so as to not move or damage the cadmium shielding sleeves at both ends. These sleeves reduce the active length of the tube

to minimize end effects. Be sure to measure both the shielded and un-shielded lengths of the counter. Slowly increase the bias voltage on the detector to 1300 V (the HP Power supply switch positions are accurate - the meter is only an indicator of the presence of voltage on the output terminal). The 10-turn FINE control should be fully counterclockwise.

Optimize the amplifier gain and the MCA LLD to minimize Dead Time produced by the extremely high count rate in the low energy "tail", but do not set the LLD so high that you lose important features. Record a spectrum. Understand and explain all of the features of the spectrum, with special attention to the relative peak heights, and the energy range and heights of the two plateaus (wall effect artifacts - Reference (1) p. 524-528, p. 533-534). Take spectra with the cadmium shields in place, and then with them removed (carefully). How do the cadmium shields influence your results? Do they have any influence on the magnitude of the incident thermal neutron flux? The measured flux density?

Replace the Cd and measure the count rate at several radial distances from the source. Does $r\phi$ fall off as $e^{-r/L}$? Deduce L and compare with the "book" value, 2.9 cm, for the thermal diffusion length. Explain the difference, if any.

STUDIES WITH A GeLi (Germanium Lithium Drifted) DETECTOR:

(A) Determine the detection efficiency of the GeLi detector using a ^{60}Co calibration disk source taped to the front face of the detector cryostat. Set full scale on the MCA slightly above 2.6 MeV. Use the relative efficiency curve for germanium (Figure 8.) to extrapolate your data at 1.33 MeV to the energy of the deuteron γ -ray. You should carefully consider the effects of any "contamination" of the spectrum by environmental "background".

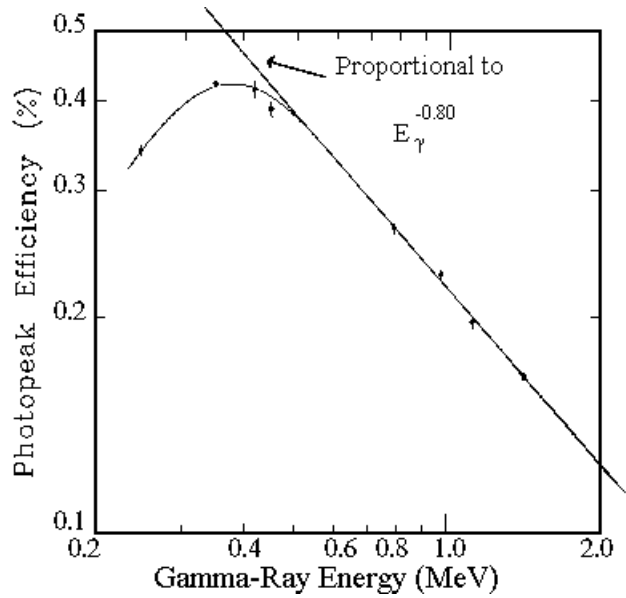


Figure 8. Relative efficiency of the Germanium detector as a function of energy, with 1/16 " Pb over the detector face.

(B) The neutron activation experiments below have two purposes: (1) the study of the decay of radioactive ^{116}In by measuring the energy and intensity of the emitted γ -rays with the GeLi detector. (2) Determine the neutron flux from the activation of the In samples.

There are three variants of the indium samples. All are mounted in protective acrylic housings.

No. 1 is a foil 25 mm diameter x 0.505 mm thick, weighing 1.846 grams. It is permanently mounted in an acrylic housing. *Activated by neutrons of all energies.*

No. 2 is a foil 25 mm diameter x 0.504 mm thick, weighing 1.834 grams sandwiched between two other indium foils of similar thickness and mass (cemented to opposite covers of the demountable housing). The outer foils act as neutron filters. *The center foil is activated by a selectively attenuated neutron flux.* (See Cross Section data in the Appendix.)

No.3 is a foil 25 mm diameter x 0.504 mm thick weighing 1.861 grams sandwiched between two cadmium foils each 0.68 mm thick (2.865 grams and 2.88 grams) that are cemented to the opposite covers of the demountable housing. The outer Cd foils of this sandwich effectively block out the thermal neutrons in the incident flux. *The center In foil is activated only by the neutrons in the resonance energy range.* (See Cross Section data in the Appendix, and Activation Foil Manual in the Reference Binder.)

The housings for the "sandwiched" In foils are easily disassembled by slipping the cap off the four locating screws - No Tools are required, or should be used. Have the T.A. demonstrate. Handle the mounts, and especially the bare foils with care. Indium is extremely soft (like warm butter) and easily deformed or defaced. It is also expensive

Expose the foils to the neutron flux by suspending them directly in the water of the moderator tank. Simply hang them by the attached strings, placing the supplied loop over the top of a 3/8" tube assembly so that the foils are at the same depth as the ^{252}Cf source, and at a radial distance of ~ 10 cm from the source. Insert all three samples at the same time and remove them in the order as above for measurements. Leave the foils in the tank for a precisely known time (3 - 6+ hours). This is vital, since the indium activity changes with time, and accurate knowledge of total exposure and the time of removal are required for meaningful interpretation of the data. You may find it convenient to load the foils into the moderator tank the morning before your afternoon laboratory session.

After an appropriate time, remove the "bare indium foil" housing from the moderator and tape it to the front face of the GeLi cryostat. Record the γ -ray spectrum, and sum the counts in the 1.27-MeV full-energy peak to determine the ^{116}In activity (use the MCA ROI/NET function). (See the ^{116}In decay scheme.) You have previously determined the detector efficiency at 1.33 MeV in Part (A) above.

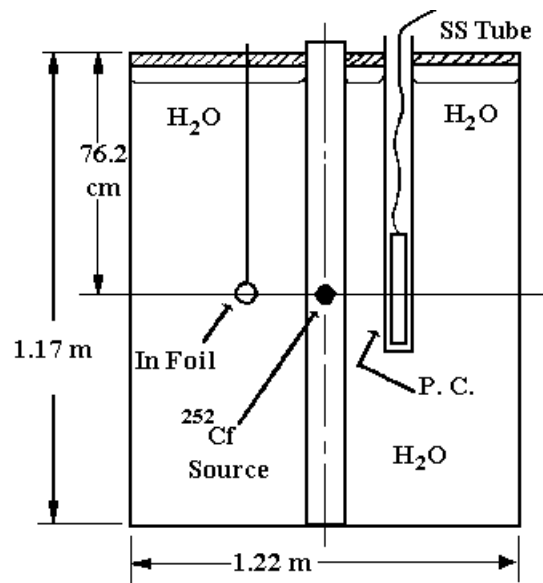


Figure 9. ^{252}Cf Neutron source mounting and moderator.

The half-life of ^{116}In is 54 minutes. From your measurements, compute the equilibrium activity that would have been produced if the foil had been exposed to the neutron flux for an "infinite" time (>10 half-lives). Also compute the equilibrium number of ^{116}In atoms in the foil. Consider the effect of the finite thickness of the foil on both the activation and decay processes.

Using the thermal-neutron cross sections for $^{116}\text{In} (n,\gamma)$ and $^{116}\text{In}^*, **$, compute the neutron flux at your exposure location. Consider the possible effects that the presence of the foil will have on the neutron-flux distribution in the immediate vicinity of the foil.

Repeat these measurements of induced activity in the indium foils shielded by indium and by cadmium. Disassemble the foil mounts carefully and **place the fragile In foil into the plastic bag provided**, and tape that bag to the front face of the GeLi detector cryostat. ***DO NOT put the tape directly on the foil - it is extremely soft and fragile.*** Explain your results. Consider the effect of the cadmium foils on the neutron flux in the vicinity of the foil assembly. Be sure to replace the foils in their respective mounting assemblies when finished counting.

QUESTIONS

- (1) What is the mechanism by which γ rays of the energies seen in this experiment (^{60}Co) deposit their energy in the germanium detector?
- (2) If you wanted to determine the energy of neutrons in the eV to keV range by a time-of-flight technique to a 1% uncertainty (1 standard deviation), and you had a device with a time resolution of 200 ps, what flight-path lengths would be required?

REFERENCES

- (1) G. F. Knoll, *Radiation Detection and Measurement*, (John Wiley & Sons, 1979), pp. 71-73, Chap. 14, pp. 765-773, and 2nd edition (1989).
- (2) N. Tsoulfanidis, *Measurement and Detection of Radiation*, (Hemisphere Publishing Corp., 1983), pp. 155-162, Chap. 14, Chap. 15, pp. 433-439.
- (3) C. M. Lederer and V. S. Shirley, *Table of Isotopes*, 7th Edition, (Wiley-Interscience, 1978) and 8th edition with CD-ROM (1996, updated 1998).
- (4) E. Segre, *Nuclei and Particles*, 2nd Edition, (Benjamin/Cummings Publishing Co., 1977), Chapter 12.
- (5) R. D. Evans, *The Atomic Nucleus*, (McGraw-Hill Book Company, 1955), Chapter 13.
- (6) *Activation Foil Manual*, 1965, Reactor Experiments, Inc.
- (7) National Nuclear Data Center Website (www.nndc.bnl.gov).