Fostering Cross-Disciplinary Research at the Madison Accelerator Laboratory (MAL)

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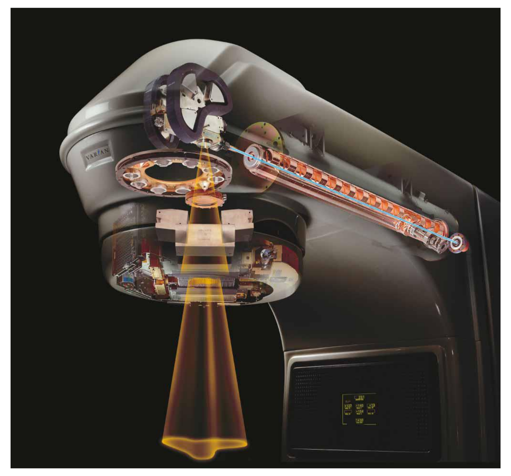
Abstract

This work explores opportunities for using X-rays produced at the Madison Accelerator Laboratory (MAL) for basic and applied research in a variety of fields, including nuclear astrophysics, materials science, geology, art history, archaeology, accelerator and medical physics. MAL is intended to be a multidisciplinary research user facility available for all JMU faculty and students as well as for higher education institutions in Virginia and beyond. Photoactivation analysis (PAA), the experimental procedure in use at MAL, is a versatile tool for a range of applications. By activating nuclei in a given sample with high-energy X-rays, we measure the decay of the radioactive isotopes produced. This summer, the PAA technique was applied to determine the elemental composition of meteorites from the John C Wells Planetarium and of artifacts from the Madison Art Collection. We also applied PAA to measure, with a high degree of precision, half-lives of isotopes relevant to nuclear astrophysics. Moreover, we successfully carried out radiation dose measurements to confirm the current 6 and 15 MeV linac energies available at MAL. These results establish a standard for future dose measurements to allow characterization of intermediate energies to be available at MAL in the future.

JMU's Medical Electron Linear Accelerator



Typical medical linac

What is a Linear Accelerator?

- A modern linear accelerator, or linac, is a device that uses high Radio-Frequency (3 GigaHz) electromagnetic waves to accelerate charged particles (i.e. electrons) to high energies in a linear path, inside a tube-like structure called the accelerator waveguide.

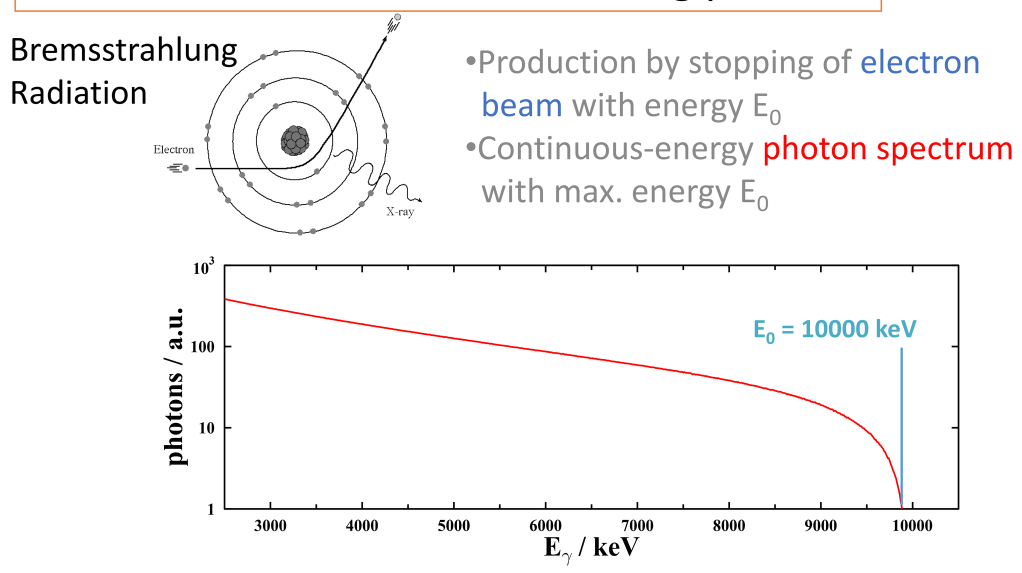
How Does it Work?

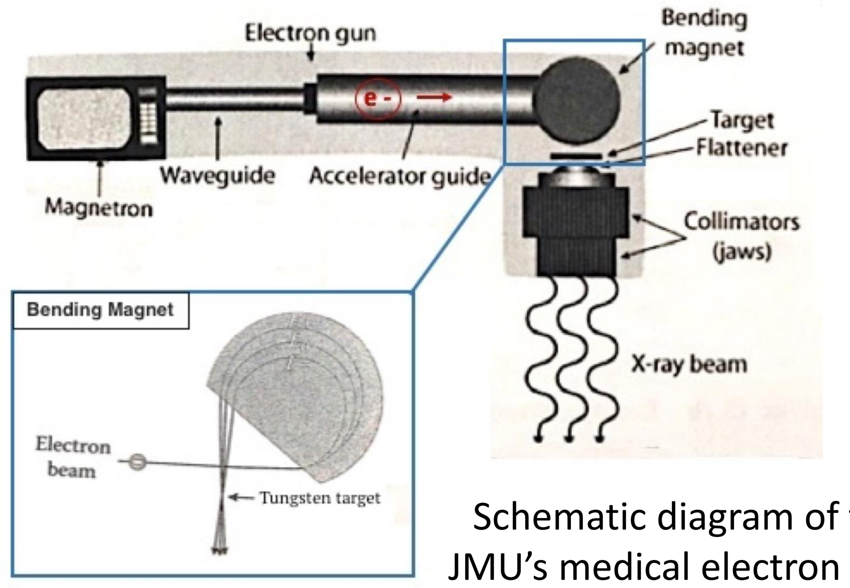
- The linac uses microwave technology to accelerate electrons in a part of the linac called the waveguide, then allows these electrons to collide with a heavy metal target (typically tungsten). As a result of these collisions, high energy X-rays are produced from the target. These x-rays are called *bremsstrahlung radiation*. Because they have a broad energy distribution they are also referred to as continuous X-rays. They make up the beam that can then be used to irradiate materials.

Major Linac Components

1. The magnetron source generates microwaves
2. The waveguide is an insulated tube that maintains the structure of the waves by reflecting them forward off the walls of the tube
3. The electron gun provides the source of electrons ejected into waveguide structure
4. The bending magnet rotates electrons 270° to strike the target. By doing this, a very small focal spot is obtained which results in an achromatic X-ray beam

Illustration of the bremsstrahlung process





Schematic diagram of the JMU's medical electron linac

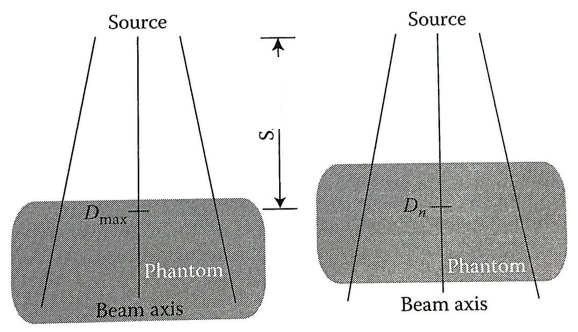
Linac Photon Energy Measurements at MAL

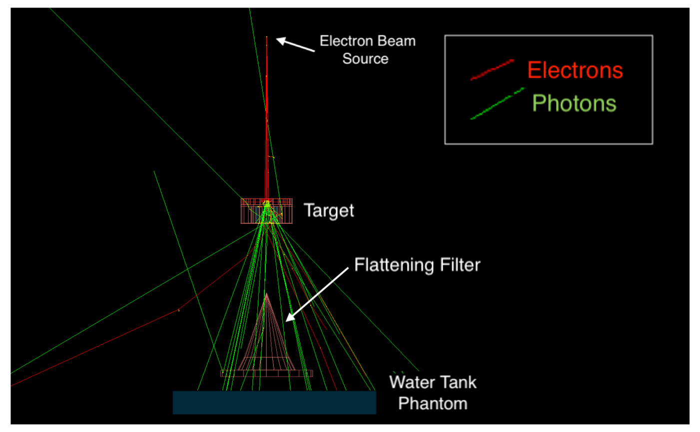
The medical linac at MAL produces 2 standard photon beams with endpoint energies of 6 and 15 MeV.

How to measure these energies?

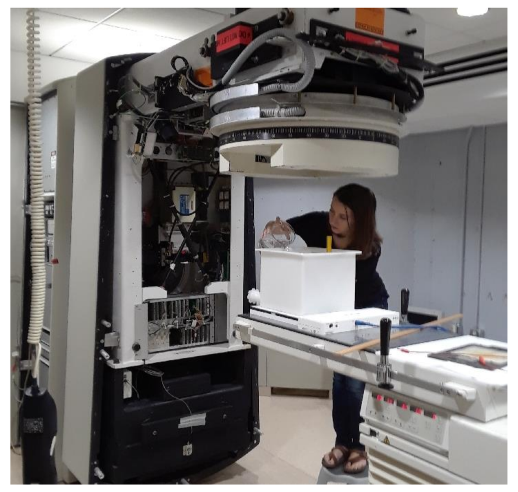
- By dose measurements made in a phantom (a human surrogate that behaves similarly toward ionizing radiation but allows placement of a detector inside).
- These dose measurements, i.e. tissue maximum ratio (TMR), are usually expressed as a fraction of the amount of radiation reaching the detector relative to another value.

$$TMR = \frac{dose\ at\ depth\ n}{dose\ at\ max\ depth}$$



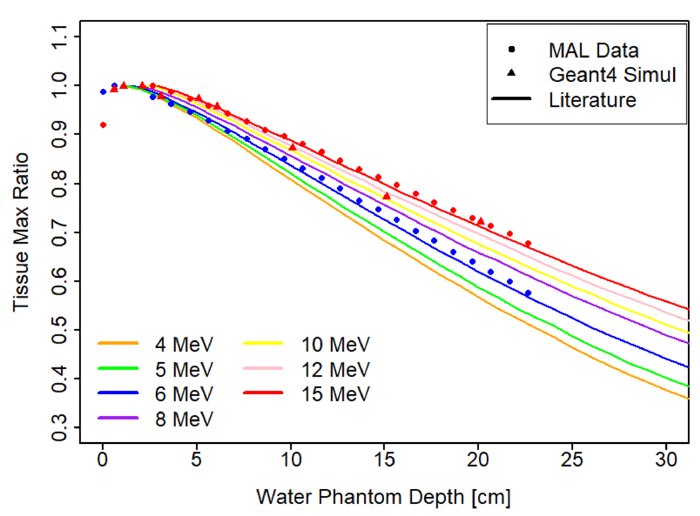


Geant4 simulations of TMR were made to investigate the possibility of operating at intermediate energies at MAL



A tank with varying water levels was used as a phantom for the TMR measurements

Preliminary Results of the TMR measurements

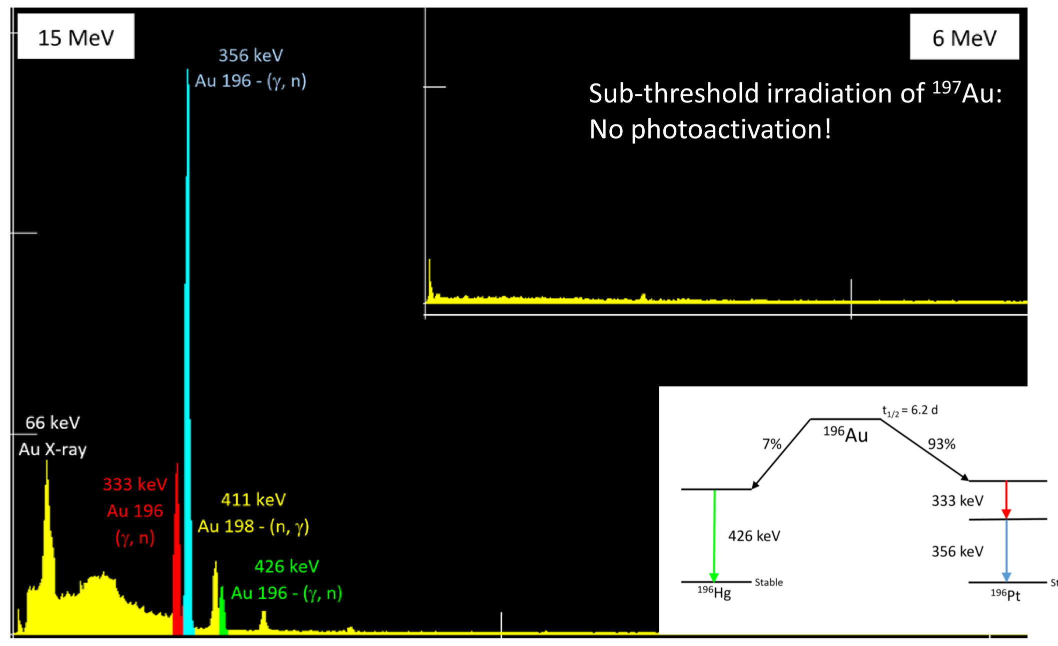


Photoactivation Analysis Technique

- Photon Activation Analysis (PAA) is a versatile tool that provides high sensitivity for detecting the vast majority of the elements in the periodic table.
- PAA offers two key advantages as a research tool: it can probe materials that are difficult to treat chemically and it is very well suited for investigating minute samples (sub-milligram) to very large ones (in the kilogram range).
- The process entails exposing the sample to high-energy photons; as a result, nuclei in the sample will become activated and decay by emitting characteristic radiations. The characteristic decays are then measured with detectors.

Proof of Concept of the PAA Technique:

- Photodisintegration of ^{197}Au stable isotope: $\gamma + {}^{197}\text{Au} \rightarrow {}^{196}\text{Au}^{*} + \text{neutron}$
- A Greek gold coin was irradiated at both the 6 and 15 MeV photon settings. The threshold energy to produce the ^{196}Au radioactive isotope of gold is 8 MeV, thus no activity was detected with 6 MeV photons. As the spectrum to the right shows, the three main energies characteristic of the ^{196}Au decay were detected from irradiation at 15 MeV.



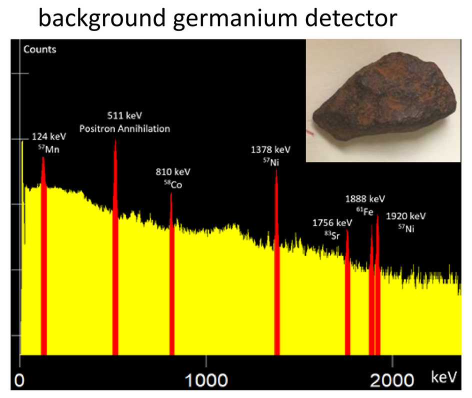
Energy spectrum of the gold coin after being irradiated with standard photon beam energies at MAL

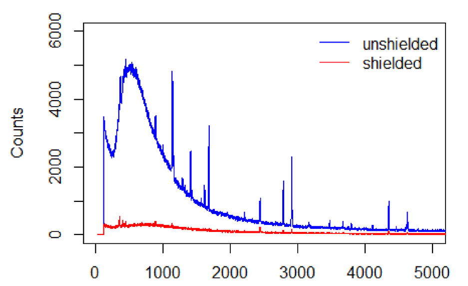
Experimental Setup for Offline Counting

Ultra-low background Ge detector with Greek gold stater of Alexander the Great, c. 330 BCE

PAA Applications at MAL

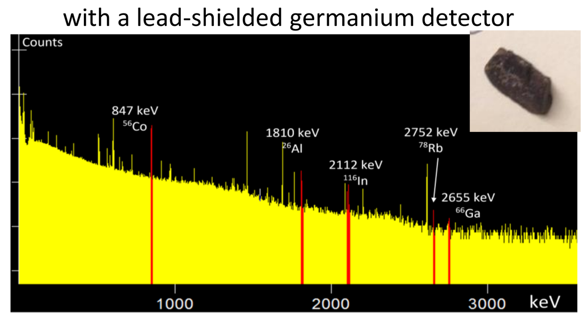
Energy spectrum of a 13.2g iron meteorite measured with an ultra-low background germanium detector



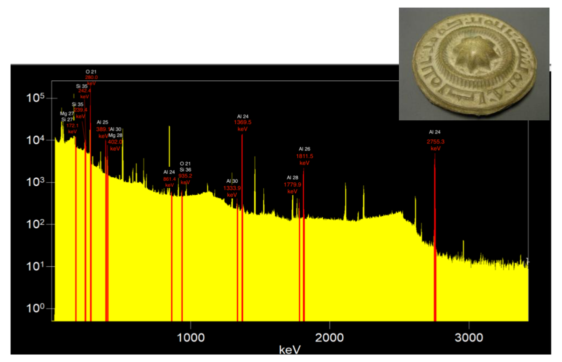


Background energy spectrum in offline counting room

Energy spectrum of a 1.44g meteorite with a lead-shielded germanium detector

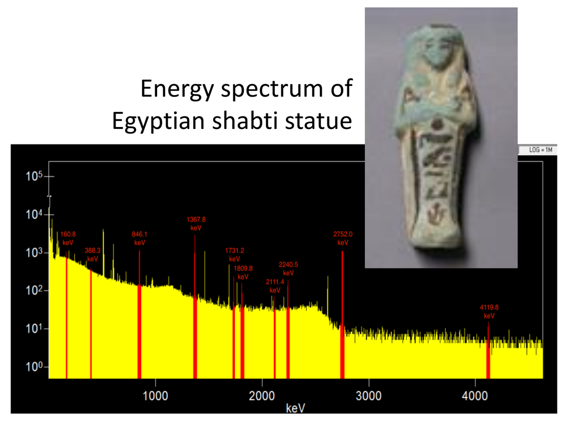


Lead bricks were used to build a shield to reduce background radiation during the measurements in the offline counting room.



Energy spectrum of a clay Islamic prayer seal measured with a lead-shielded germanium detector

Energy spectrum of Egyptian shabti statue



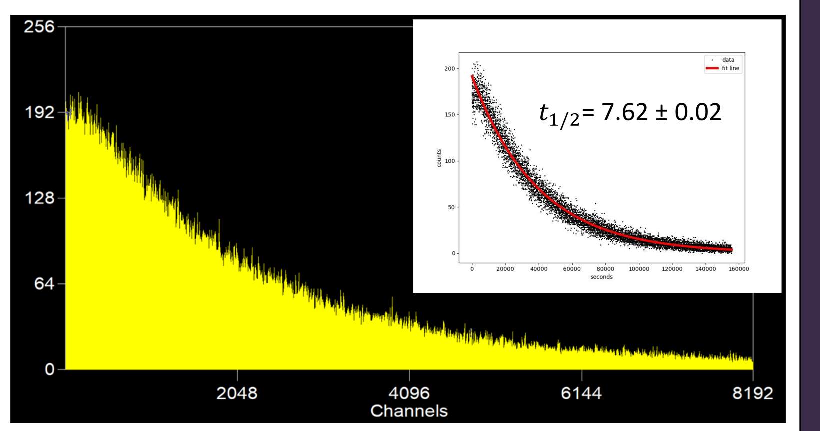
Half-life Measurements

- The half-life ($t_{1/2}$) is defined as the time required for the number of radioactive atoms in a sample to decay to half the initial value:

$$N(t) = N_0 e^{-\frac{\ln(2)}{t_{1/2}} * t}$$

- This gives a measure of how quickly the isotope decays in time, and is unique to each radioactive isotope.

Data and fit for the activity of a sample of ^{73}Se, whose half-life was determined to be 7.62 ± .02 hours.



Conclusions & Outlook

- Several artifacts from the Madison Art Collection as well as meteorites from the John C. Wells Planetarium were subjected to the photoactivation technique. The corresponding elemental composition of these objects was successfully resolved.
- PAA was also successfully applied to measure half-lives of isotopes relevant to nuclear astrophysics with a high degree of precision.
- Moreover, we successfully carried out radiation dose measurements to confirm the current 6 and 15 MeV linac photon energies available at MAL. These results establish a standard for future dose measurements to allow characterization of intermediate energies to be available at MAL in the future. Preliminary Geant4 Monte Carlo simulations for the 6 and 15 MeV standard energies support our experimental results for dose measurements, and will guide future investigations to establish these intermediate energies.

Acknowledgements

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Artifacts provided by the Madison Art Collection

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