Developing Madison Accelerator Laboratory (MAL) as a Unique Nuclear Research User Facility at James Madison University

https://sites.lib.jmu.edu/mal

Adriana Banu – MAL Scientific Coordinator
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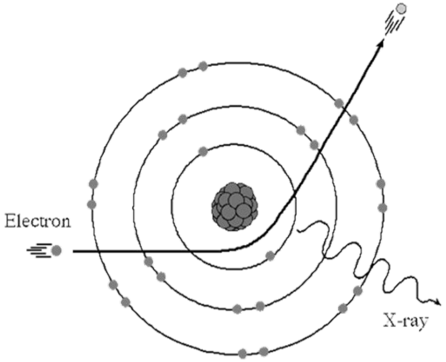
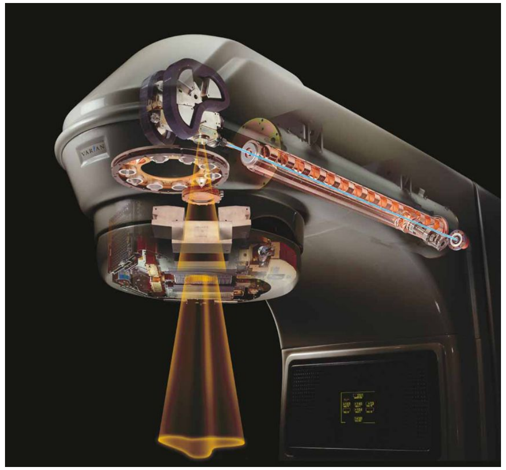
Working Group on Facilities, Instruments & Upgrades
2022 NSAC Long Range Plan Town Hall Meeting on Nuclear Structure, Reactions and Astrophysics
Nov 14-16, Argonne National Laboratory

MAL: History and Mission

- James Madison University is an R2 university located in Harrisonburg, VA (in the beautiful Shenandoah Valley)

- Dept. of Physics and Astronomy is an undergraduate-only department
  - The department acquired **a medical electron linear accelerator (linac)** and an **X-ray imaging machine** from the former Cancer Therapy Center of the Rockingham Memorial Hospital.
  - In March **2018**, MAL became **officially licensed for operations** by the VA Dept. of Health
  - In September **2022**, MAL **joined ARUNA**





MAL mission is two-fold:

- Our **research-focused mission** is to repurpose and transform an "off-the-shelf" medical electron linear accelerator, originally used for clinical operations, into a multidisciplinary user-research facility available for all JMU faculty and students as well as for other higher-education institutions and research facilities in Virginia and beyond.
- Our **education-focused mission** is to forge collaborations between the physics, nuclear engineering and health science departments across the state of Virginia and beyond that focus on the development of a broad educational curriculum in applied photon science and accelerator or medical physics.

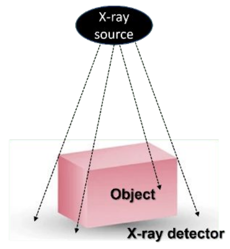
Madison Accelerator Laboratory

Medical electron linear accelerator (linac)

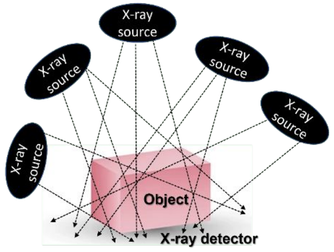
- **Siemens Magnetron-based linac (3 GHz RF frequency)**
  - Dual Photon Beam (6 & 15 MV)
  - Multi-Energy Electron Beams (5, 7, 8, 10, 12, and 14 MeV)
- **Electron Beam Characteristics:**
  - Pulsed 3 μs beam at 200(10) Hz pulse repetition frequency
  - Beam current: 0.1 – 10 mA avg, 0.15-1.5 A peak
- **Bremsstrahlung Target:** Tungsten
- **Dose rate:** ~3 Gy/min (photons), ~9 Gy/min (electrons) at isocenter
- **Beam profile:** up to 40 cm x 40 cm flat field at isocenter (reduceable with collimators)
- **Instrumentation:**
  - Suite of HPGe detectors w/ rel. efficiencies up to 60%, ultra-low background shielding
  - Suite of NaI(Tl) with analog/digital base
  - Silicone surface-barrier detectors with fast/slow preamplifiers
  - Standalone DAQ systems (*i.e.*, Genie 2000 (Mirion), CAEN DT5725S digitizer)

X-Ray imaging machine

- Nucletron Simulix X-ray imager used to simulate the radiation used for cancer treatment.
- X-ray energies in the 40-120 KeV range. They penetrate densities close to water but not denser like bone or metal.
- X-ray source equipped with imaging software that provides both 2D & 3D radiographs



2D radiograph from a *fixed-angle* X-ray source



3D radiograph from a *variable-angle* X-ray source

Basic Research @ MAL

- Basic research in ***Nuclear Astrophysics (under development):***

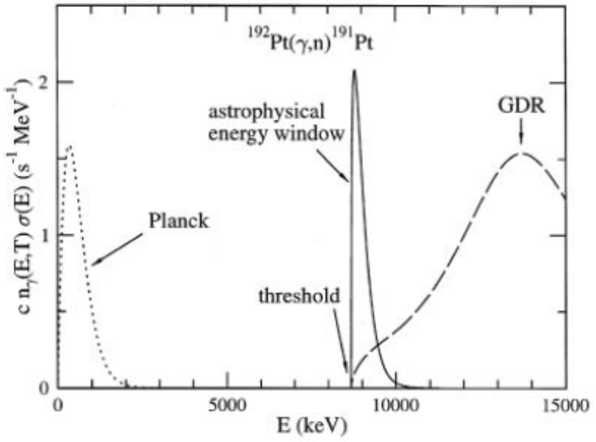
  Exploring the origin of the rarest stable isotopes via photon-induced activation studies

  - Measurements of ground state reaction rates for photo-neutron reactions relevant to the *p*-process nucleosynthesis
  - Our objective is to compare experimental data to calculated ground-state reaction rates and cross sections in Hauser-Feshbach statistical reaction models.
  - The ultimate goal here is to improve the knowledge of the dipole γ-strength functions.

The reaction rate for a photodisintegration reaction

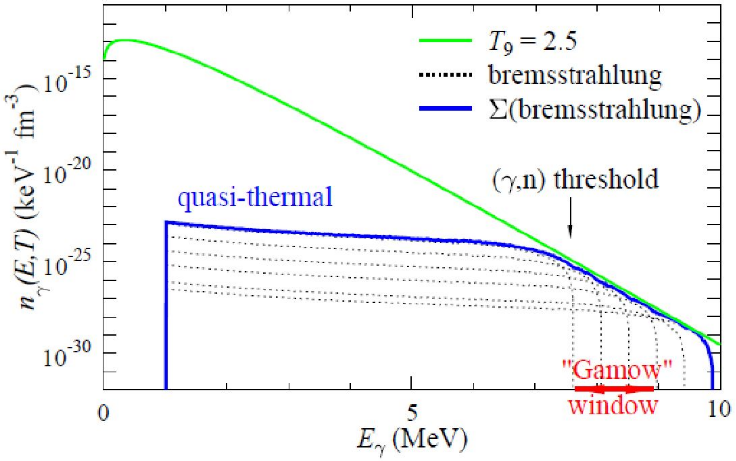
$$\lambda(T)=\int_0^\infty c n_\lambda^{Planck}(E,T)\sigma(E)dE$$

$$n_\gamma^{Planck}(E,T)=\left(\frac{1}{\pi}\right)^2\left(\frac{1}{\hbar c}\right)^3\frac{E^2}{\exp(E/kT)-1}$$



P. Mohr et al. (Phys. Lett. B 488, (2000))

'The superposition method'



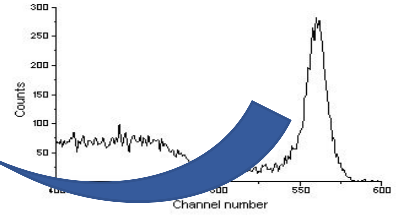
$$c n_\gamma^{Planck}(E,T)\approx\sum_i a_i(T)\Phi_\gamma^{brems}(E,E_{\max,i})$$

$$\lambda_{(\gamma,n)}^{gs}(T)\approx\sum_i a_i(T)\int_{E_{thr}}^{E_{\max,i}}\Phi_\gamma^{brems}(E,E_{\max,i})\sigma_{(\gamma,n)}(E)dE$$

$$\lambda_{(\gamma,n)}^{gs}(T)\approx\sum_i a_i(T)I_{\sigma_{(\gamma,n)},i}$$

$$\gamma+{}^{A}X\rightarrow{}^{A-1}X^*+n$$

$$A_\gamma=N_T\varepsilon_\gamma I_\gamma p\frac{t_{life}}{t_{real}}\frac{\left(1-e^{-\lambda t_{irr}}\right)}{\lambda t_{irr}}e^{-\lambda t_{cool}}\left(1-e^{-\lambda t_{meas}}\right)I_{\sigma(\lambda,n)}$$



Half-Life Measurements @ MAL

High-precision measurements of half-lives for ^{69}Ge, ^{73}Se, ^{83}Sr, ^{85m}Sr, and ^{63}Zn radionuclides relevant to the astrophysical *p*-process via photoactivation at the Madison Accelerator Laboratory

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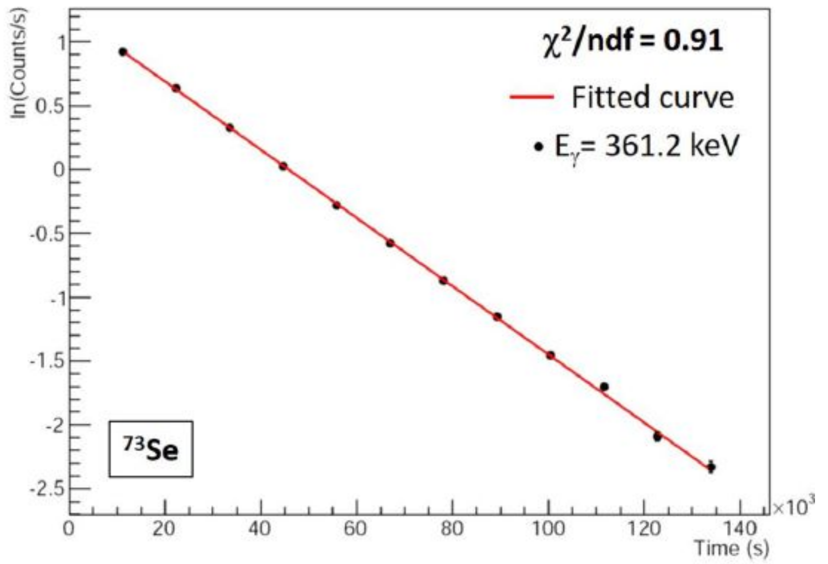
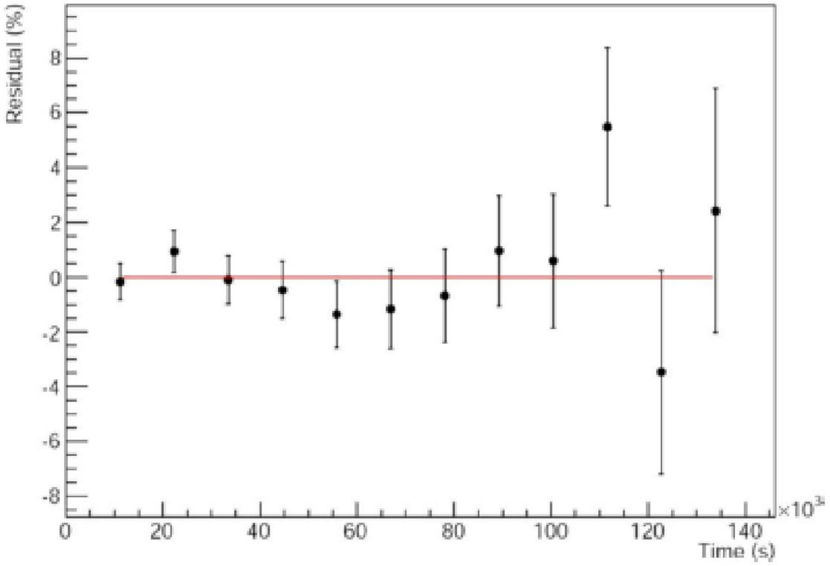
Abstract
The ground state half-lives of ^{69}Ge, ^{73}Se, ^{83}Sr, ^{63}Zn, and the half-life of the 1/2$^-$ isomer in ^{85}Sr have been measured with high precision using the photoactivation technique at an unconventional bremsstrahlung facility that features a repurposed medical electron linear accelerator. The γ-ray activity was counted over about 6 half-lives with a high-purity germanium detector, enclosed into an ultra low-background lead shield. The measured half-lives are: $T_{1/2}(^{69}\mathrm{Ge}) = 38.82 \pm 0.07$ (stat) ± 0.06 (sys) h; $T_{1/2}(^{73}\mathrm{Se}) = 7.18 \pm 0.02$ (stat) ± 0.004 (sys) h; $T_{1/2}(^{83}\mathrm{Sr}) = 31.87 \pm 1.16$ (stat) ± 0.42 (sys) h; $T_{1/2}(^{85m}\mathrm{Sr}) = 68.24 \pm 0.84$ (stat) ± 0.11 (sys) min; $T_{1/2}(^{63}\mathrm{Zn}) = 38.71 \pm 0.25$ (stat) ± 0.10 (sys) min. These high-precision half-life measurements will contribute to a more accurate determination of corresponding ground-state photoneutron reaction rates, which are part of a broader effort of constraining statistical nuclear models needed to calculate stellar nuclear reaction rates relevant for the astrophysical *p*-process nucleosynthesis.





J. Radioanalytical and Nuclear Chemistry 32, 1113 (2021)

Applied Research @ MAL

A few applications are being developed such as:

- *Archaeometry with Photon Activation Analysis (PAA)*

- *Evaluation of Oxides and Au-Supported Oxides as Potential Radiosensitizer Nanomaterials*
  - ❖ *The use of nanomaterials for medical applications represents an advantageous approach to decrease side effects*
  - ❖ *Facilities such as MAL are needed for academic research of this category since access to hospital LINACs is restricted*

- *Studies of X-Ray Radiation Enhancing and Radioluminescence of Novel Metals and Lanthanide-Based Nanocomposites*
  - ❖ Research Collaboration with Jessika Rojas (VCU) – 2022 -> 2025

- *Non-Destructive Electron Beam Diagnostics*

Biomedical Applications @ MAL

Radiocatalytic performance of oxide-based nanoparticles for targeted therapy and water remediation

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A R T I C L E I N F O

Keywords:
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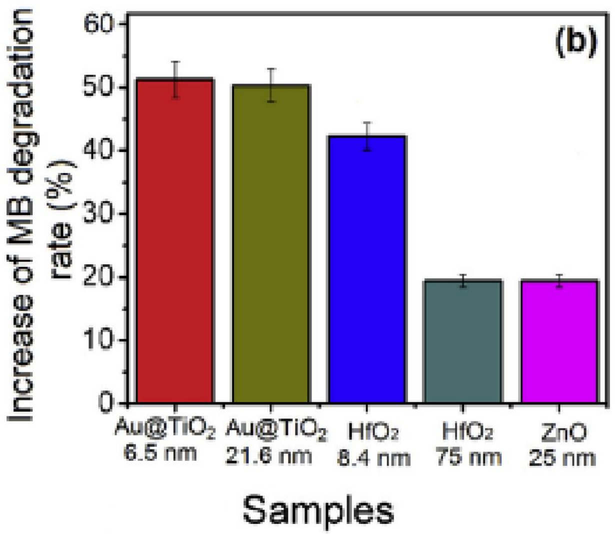
X-rays
Methylene blue
Supported gold nanoparticles
Metal oxide nanoparticles

A B S T R A C T

The radiocatalytic behavior of zinc oxide (ZnO), hafnia (HfO_2), titania (TiO_2), and gold-titania ($Au@TiO_2$) nanomaterials was investigated through the degradation of methylene blue as the organic probe. The dye degradation by X-rays from a medical linear accelerator with endpoint energy of 6 MeV was enhanced in the presence of the oxide-based nanoparticles evidencing their promise as radiosensitizers. An increase in the dye apparent reaction rate constants of ~20% and up to 82% was observed in the presence of oxides-based nanoparticles during exposure to X-rays. This enhancement is attributed to the increased production of reactive species in solution. Gold-titania nanocomposites evidenced one of the highest radiocatalytic activity among the materials under investigation, with an increase in the MB apparent reaction rate constant of 50.3%. Overall, our experiments showed that radiocatalysis with oxides-based nanoparticles is a promising concept worth exploring in applications such as targeted radiation therapy and pollutant removal of water streams.

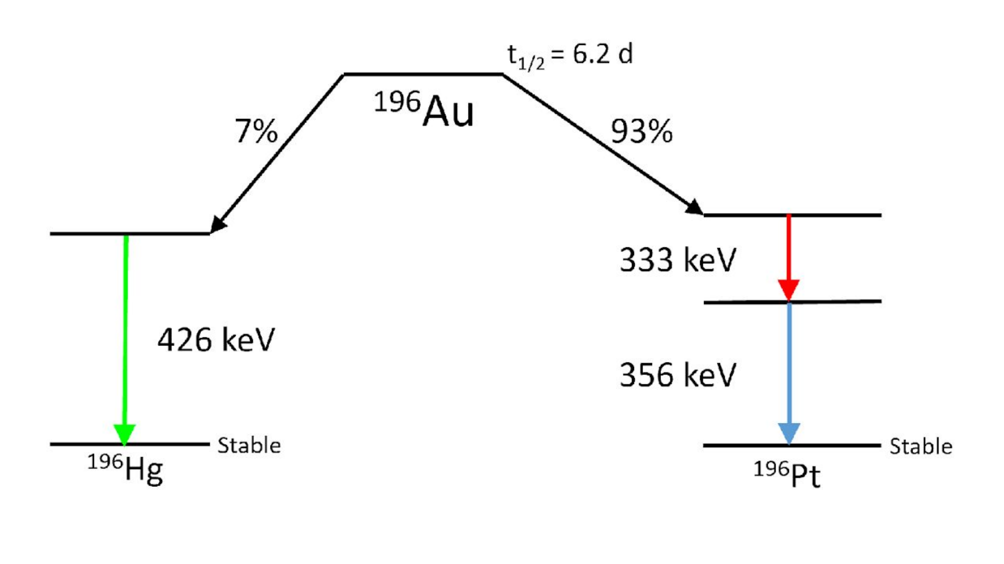


Radiation Physics and Chemistry 173,108871 (2020)

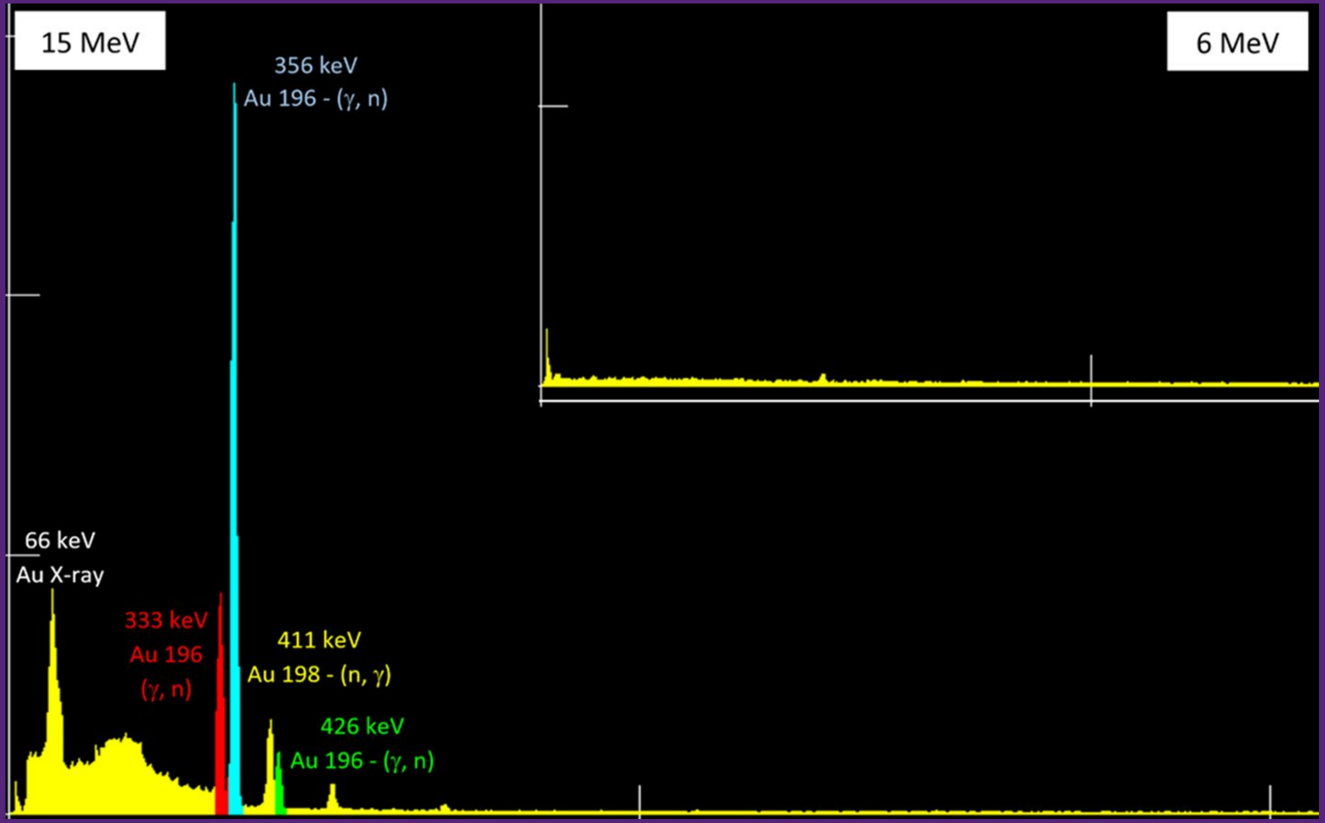
Proof of Concept of PAA

Photodisintegration of ^{197}Au (stable isotope):

$$\gamma + {}^{197}\text{Au} \rightarrow {}^{196}\text{Au}^{*} + \text{neutron}$$



A gold sample 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.

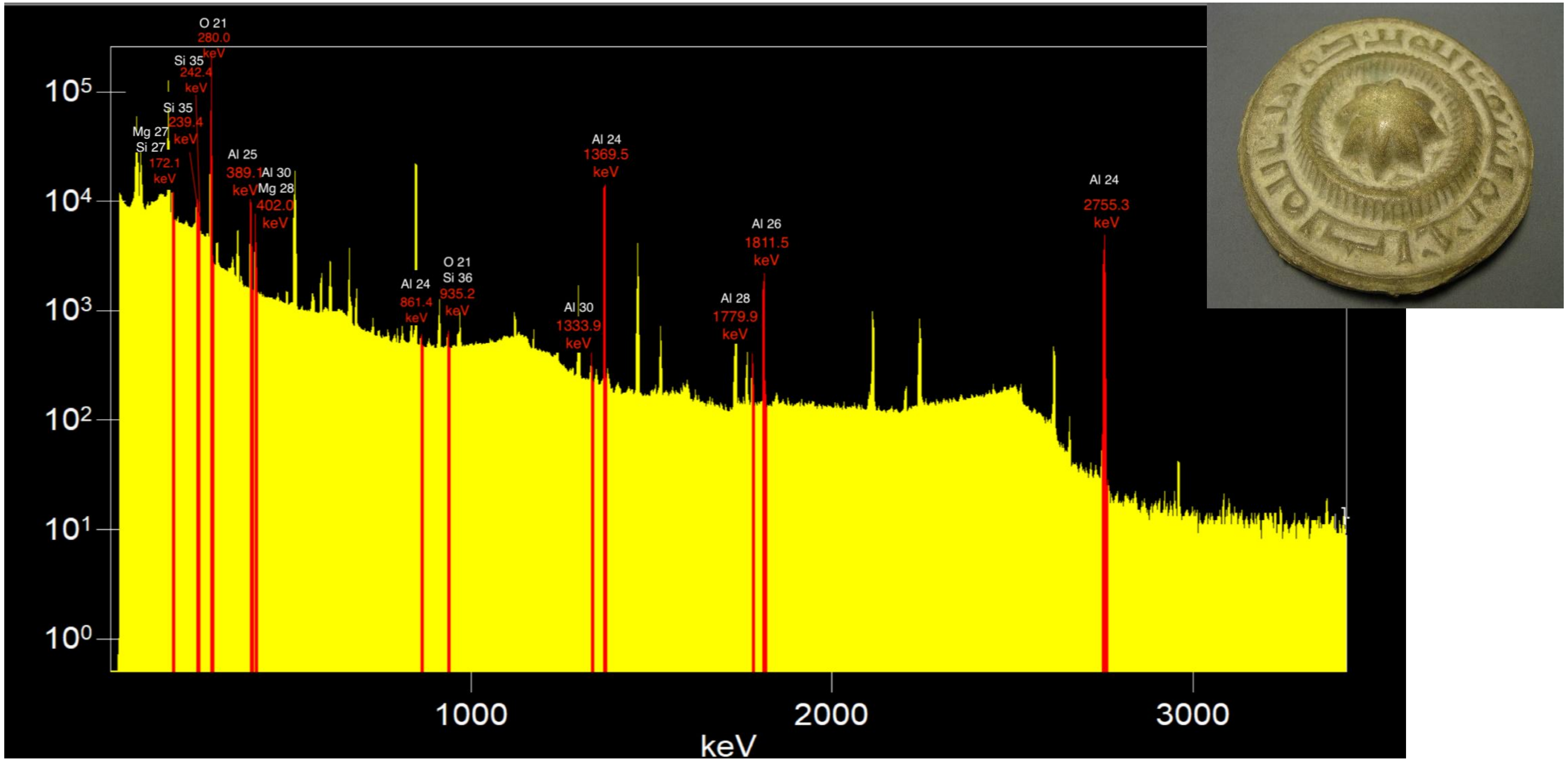


Photon Activation Analysis (PAA) @ MAL

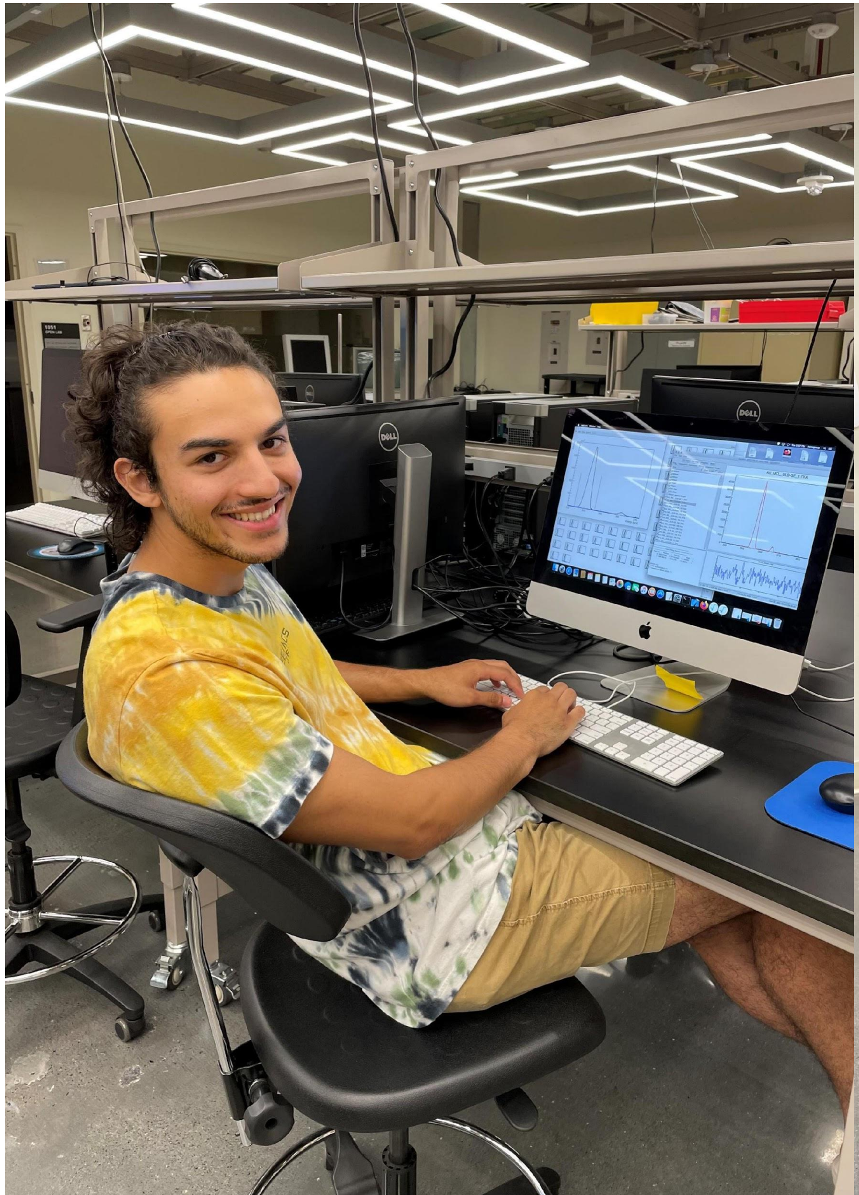
Activate samples via (γ,n) reactions and analyze γ-ray decay spectra

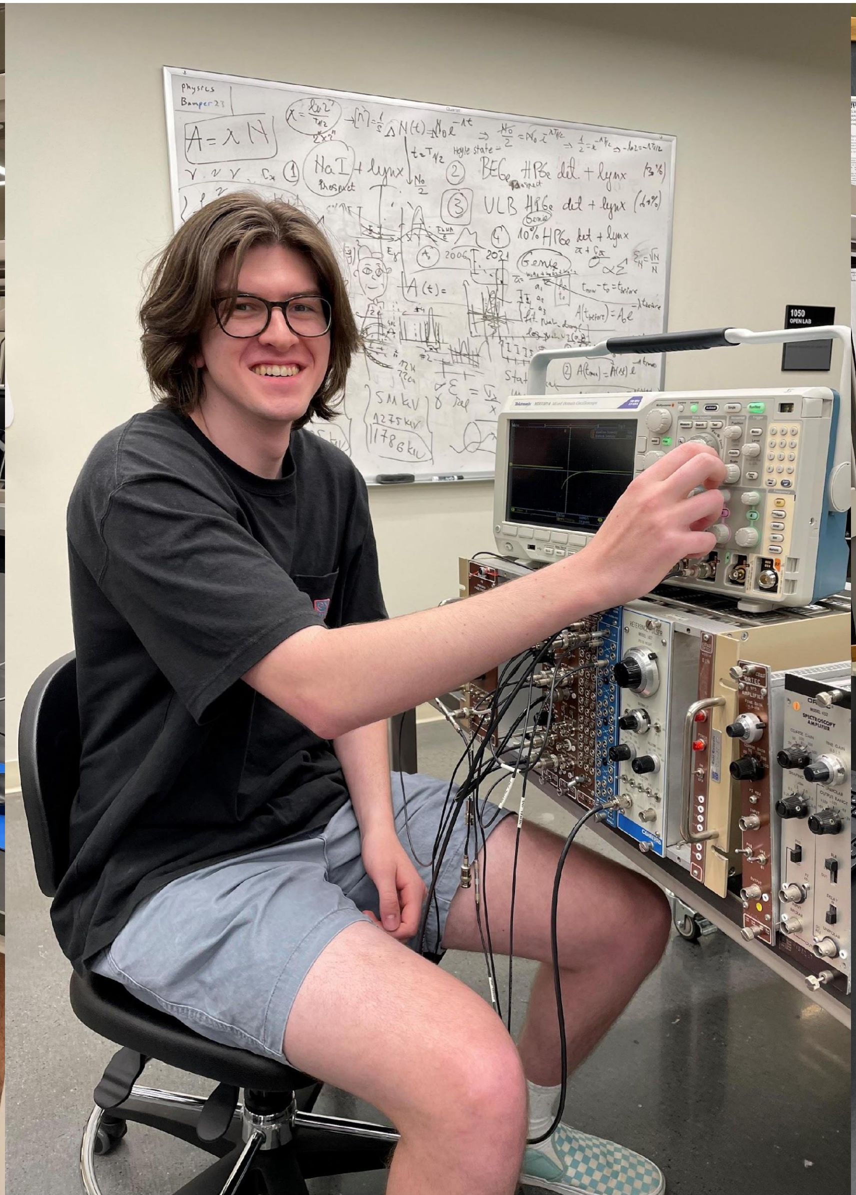
Chemical Composition Identification using PAA @ MAL

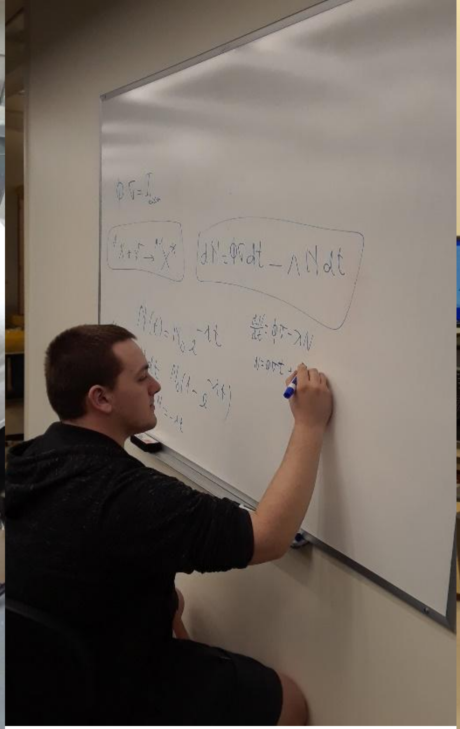
Example of an iradiated Islamic Prayer Seal made of primarily aluminum oxides

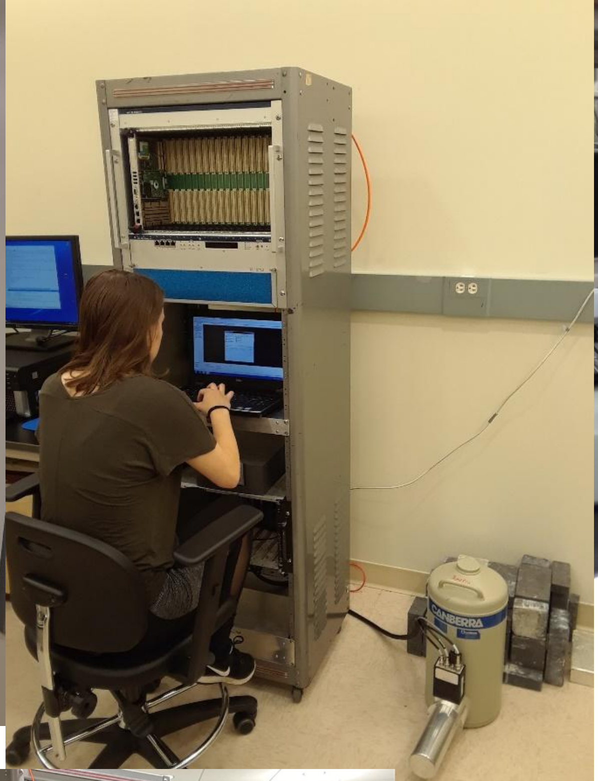


Undergraduate Research Students in Action @ MAL





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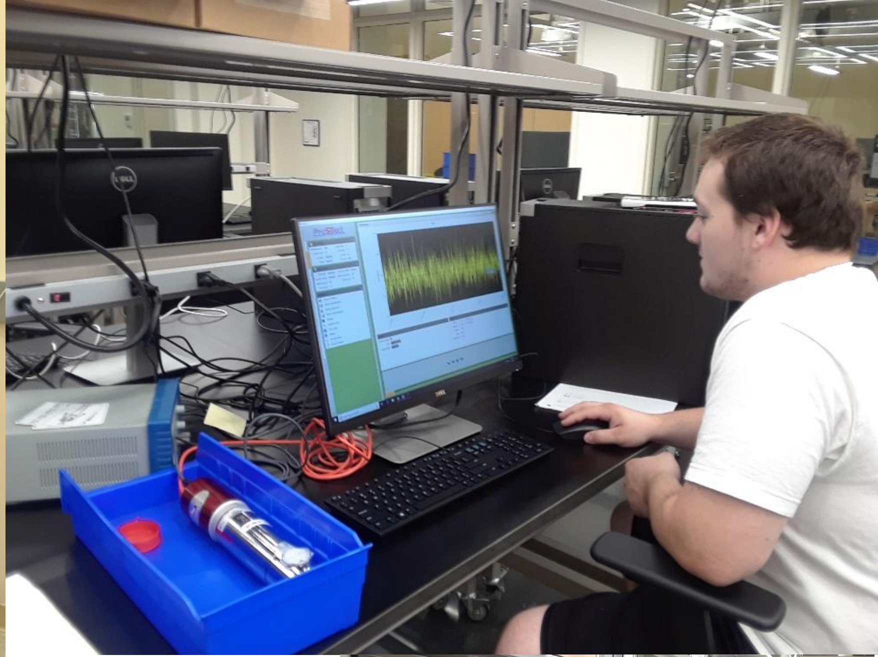

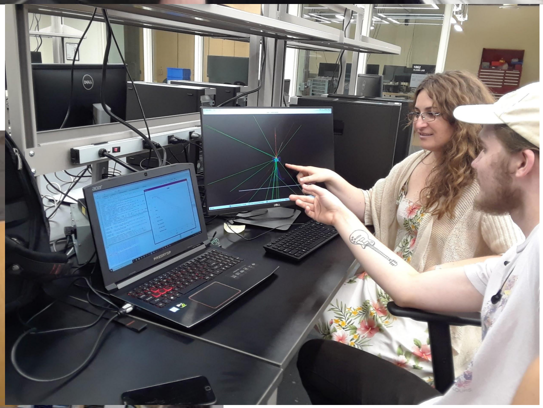


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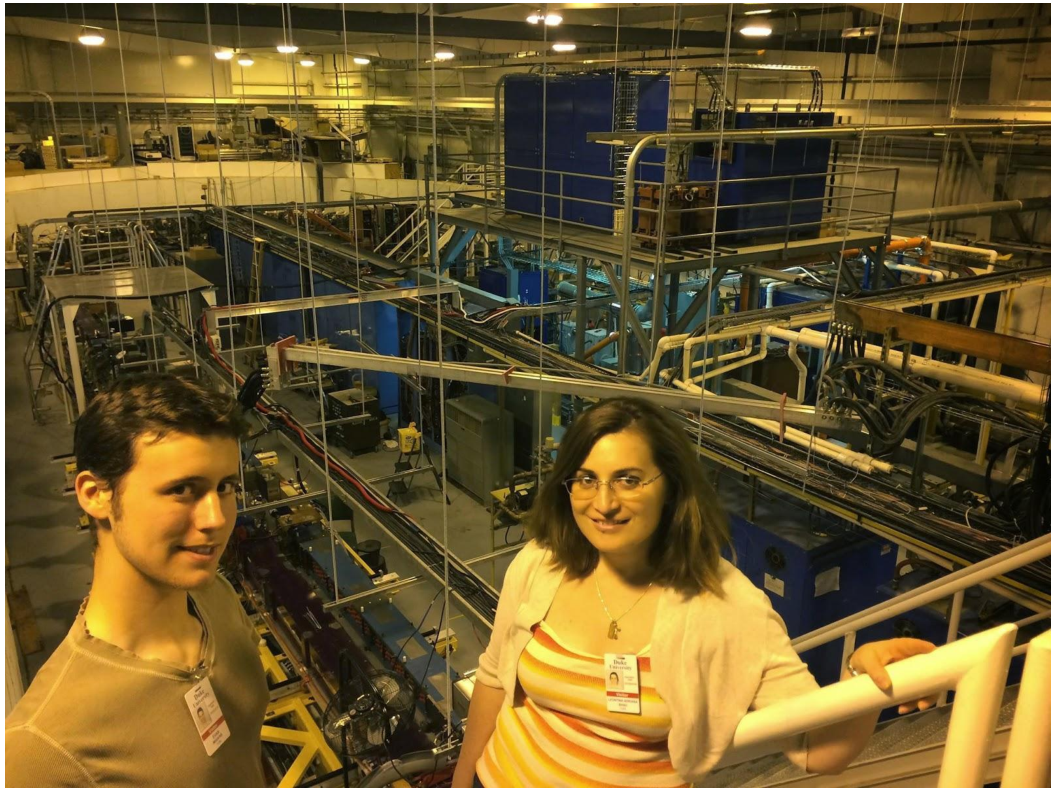
JMU Undergraduate Research Students in Action @ HIGS/TUNL



PHYSICAL REVIEW C **99**, 025802 (2019)

Photoneutron reaction cross section measurements on ^{94}Mo and ^{90}Zr relevant to the *p*-process nucleosynthesis

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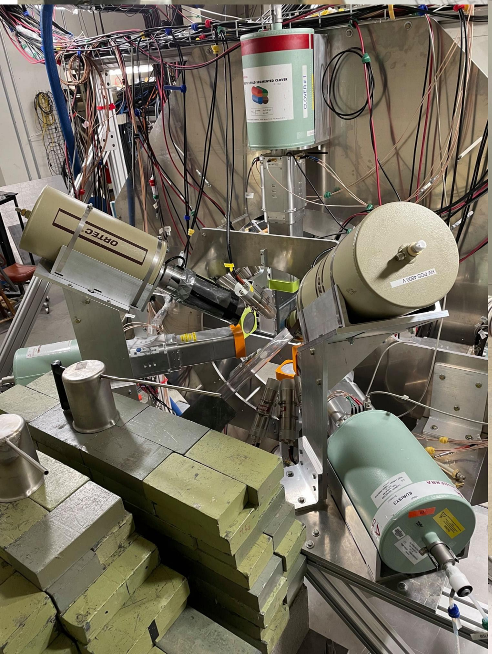


Thank You for your Attention!

Jessica Mayer (class of 2018), **Teddy Chu** (class of 2020), **Dr. Scottie Pendleton** (MAL Laboratory Manager), and **Prof. Adriana Banu** (MAL Scientific Coordinator) working with the X-ray imaging machine at MAL