Exploring the Origin of the Rarest Stable Isotopes via Photon-Induced Activation Studies at the Madison Accelerator Laboratory

Adriana Banu

Department of Physics and Astronomy, James Madison University, Harrisonburg, Virginia, USA

Association for Research at University Nuclear Accelerators

2024 International Topical Meeting on Nuclear Applications of Accelerators

March 17th – 21st, 2024, Norfolk, VA, USA, hosted by Jefferson lab

MAL: History and Mission…briefly

- 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**

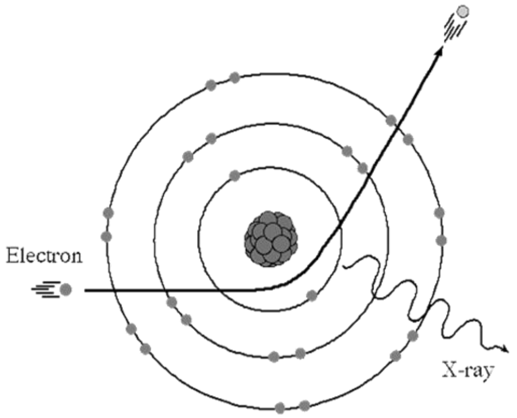
MAL mission is two-fold:

- ➢ 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.

Norfolk, Virginia
AccelApp'24

MAL (medical) electron linac – overview of its capabilities

- **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 100-300 Hz pulse repetition frequencies
  - 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)

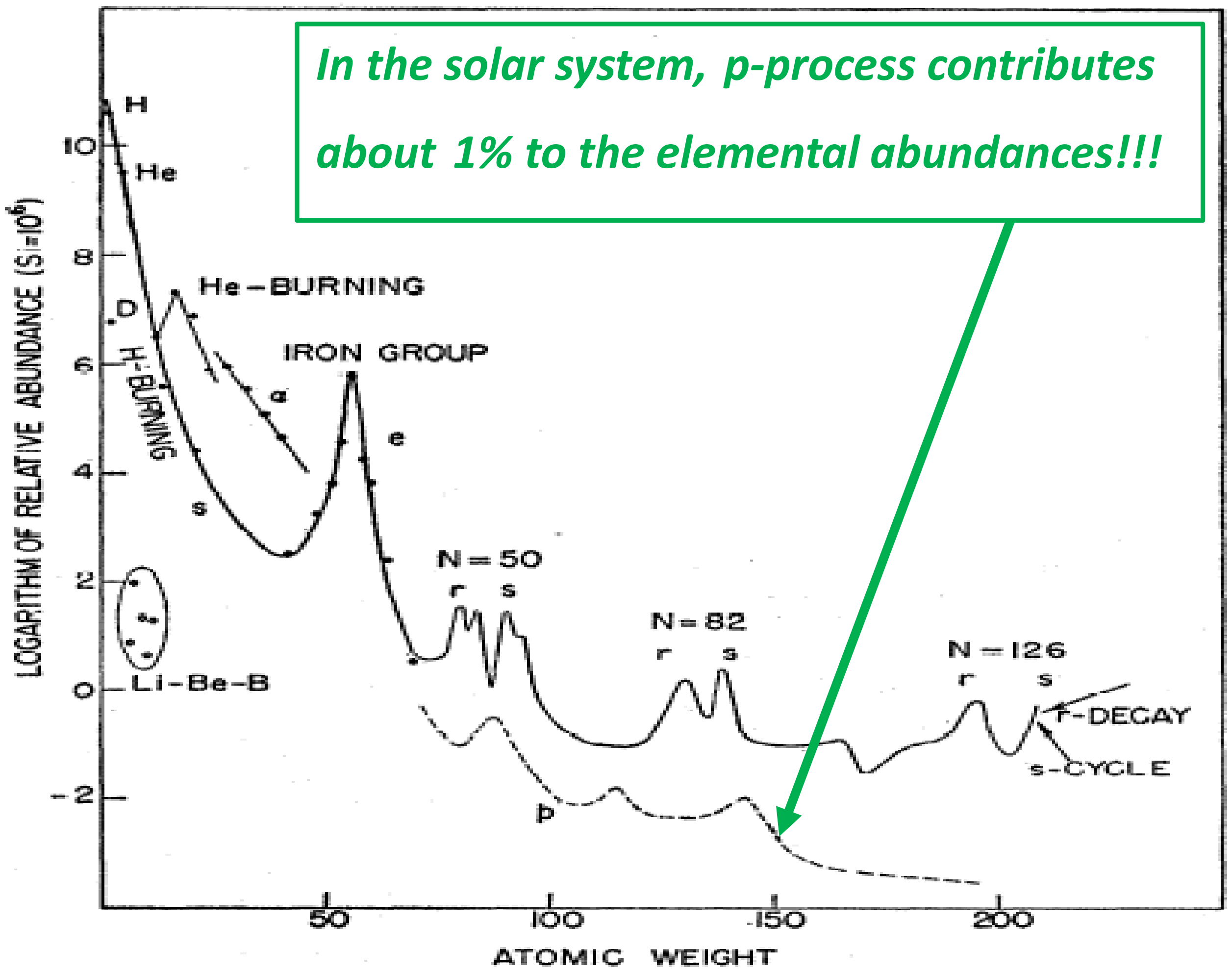


- **Associated Instrumentation:**
  - Suite of HPGe detectors w/ rel. efficiencies up to 60%, ultra-low background shielding
  - Suite of NaI(Tl) detectors with analog/digital base & LaBr3 detectors with digital base
  - Silicone surface-barrier detectors with fast/slow preamplifiers
  - Standalone DAQ systems (*i.e.*, Genie 2000 (Mirion), CAEN DT5725S digitizer)

Check out MAL website for more details: **https://sites.lib.jmu.edu/mal**

See also talk by Dr. T. Pendleton @ Compact Accelerators-1

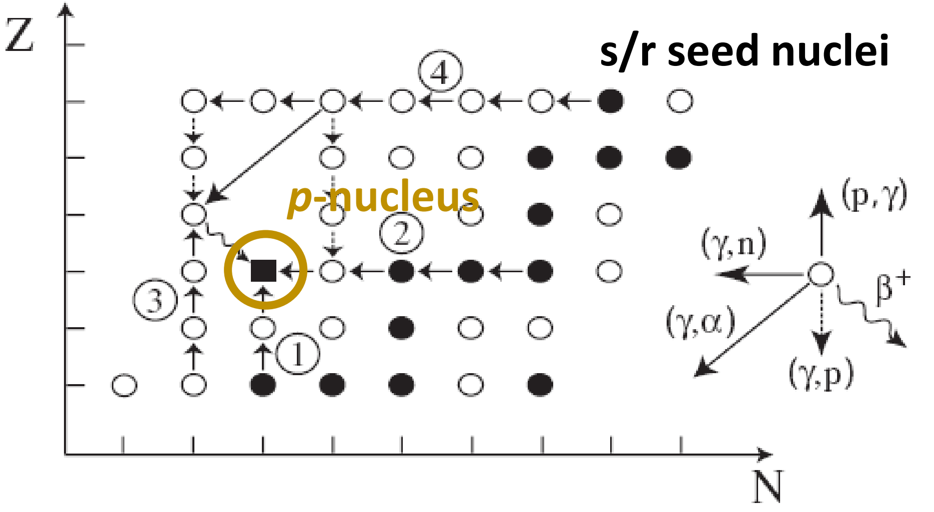
The *p*-Nuclei - 'nuclear astrophysics *p*-nuts'



B²FH, Rev. Mod. Phys. 29, 547 (1957)

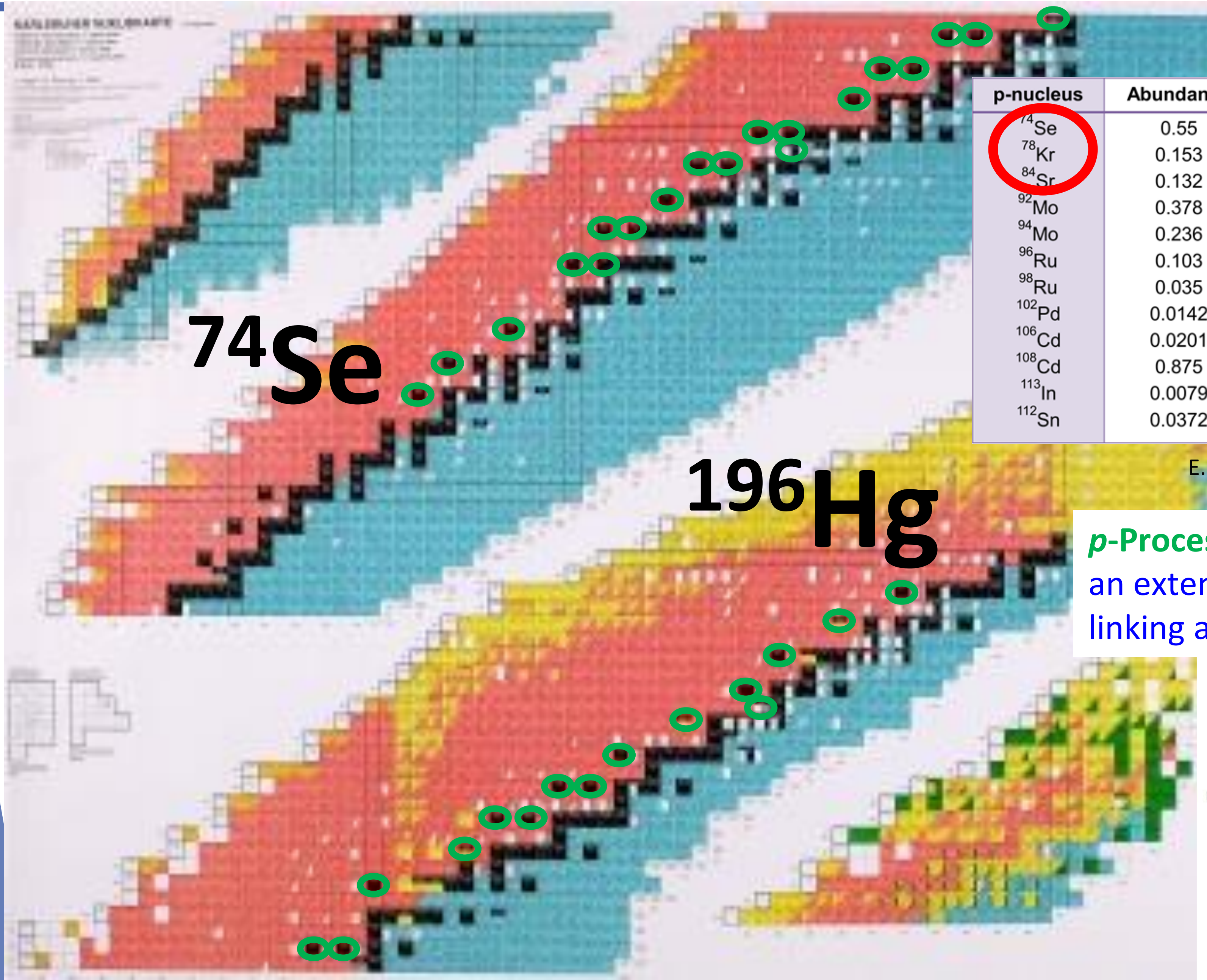
The *p*-process nucleosynthesis

- $\tau \sim 1$s & $T \sim 2\text{-}3\ 10^9$K
- Photodisintegration (γ,n), (γ,p), (γ,α)
- Type-II & Ia Supernovae



M. Arnould & S. Goriely, Phys. Rep. 384, 1 (2003)

The *p*-process nucleosynthesis is responsible for the origin of 35 proton-rich stable nuclei heavier than iron!

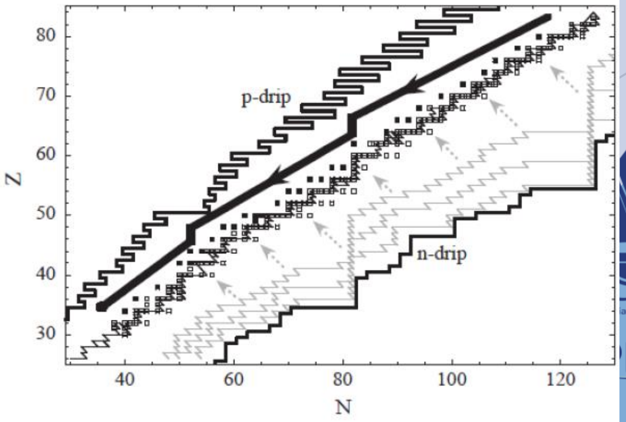


Abundances of the p-nuclei (Atoms/10^6 Si)

p-nucleus	Abundance	p-nucleus	Abundance	p-nuclues	Abundance
^{74}Se	0.55	^{114}Sn	0.0252	^{156}Dy	0.000221
^{78}Kr	0.153	^{115}Sn	0.0129	^{158}Dy	0.000378
^{84}Sr	0.132	^{120}Te	0.0043	^{162}Er	0.000351
^{92}Mo	0.378	^{124}Xe	0.00571	^{164}Er	0.00404
^{94}Mo	0.236	^{126}Xe	0.00509	^{168}Yb	0.000322
^{96}Ru	0.103	^{130}Ba	0.00476	^{174}Hf	0.000249
^{98}Ru	0.035	^{132}Ba	0.00453	^{180}Ta	2.48E-06
^{102}Pd	0.0142	^{138}La	0.000409	^{180}W	0.000173
^{106}Cd	0.0201	^{136}Ce	0.00216	^{184}Os	0.000122
^{108}Cd	0.875	^{138}Ce	0.00284	^{190}Pt	0.00017
^{113}In	0.0079	^{144}Sm	0.008	^{196}Hg	0.00048
^{112}Sn	0.0372	^{152}Gd	0.00066		

E. Anders, N. Grevesse, Geochim. Cosmochim. Acta 53, 197 (1989)

***p*-Process Nucleosynthesis:**
an extended network of some 20000 reactions linking about 2000 nuclei in the A ≤ 210 mass range



Basic Bremsstrahlung Research @ MAL for Nuclear Astrophysics (under development)

❖ **Measurements of (γ,n) reaction rates on stable proton-rich nuclei with reaction threshold around 12 MeV!**

$^{74}Se(\gamma,n)^{73}Se$

$T_{1/2} = 7.15h$

$^{78}Kr(\gamma,n)^{77}Kr$

$T_{1/2} = 74.4m$

$^{84}Sr(\gamma,n)^{83}Sr$

$T_{1/2} = 32.41m$

$^{80}Kr(\gamma,n)^{79}Kr$

$T_{1/2} = 35.04h$

$^{64}Zn(\gamma,n)^{63}Zn$

$T_{1/2} = 38.47m$

$^{70}Ge(\gamma,n)^{69}Ge$

$T_{1/2} = 39.05h$

$^{86}Sr(\gamma,n)^{85}Sr$

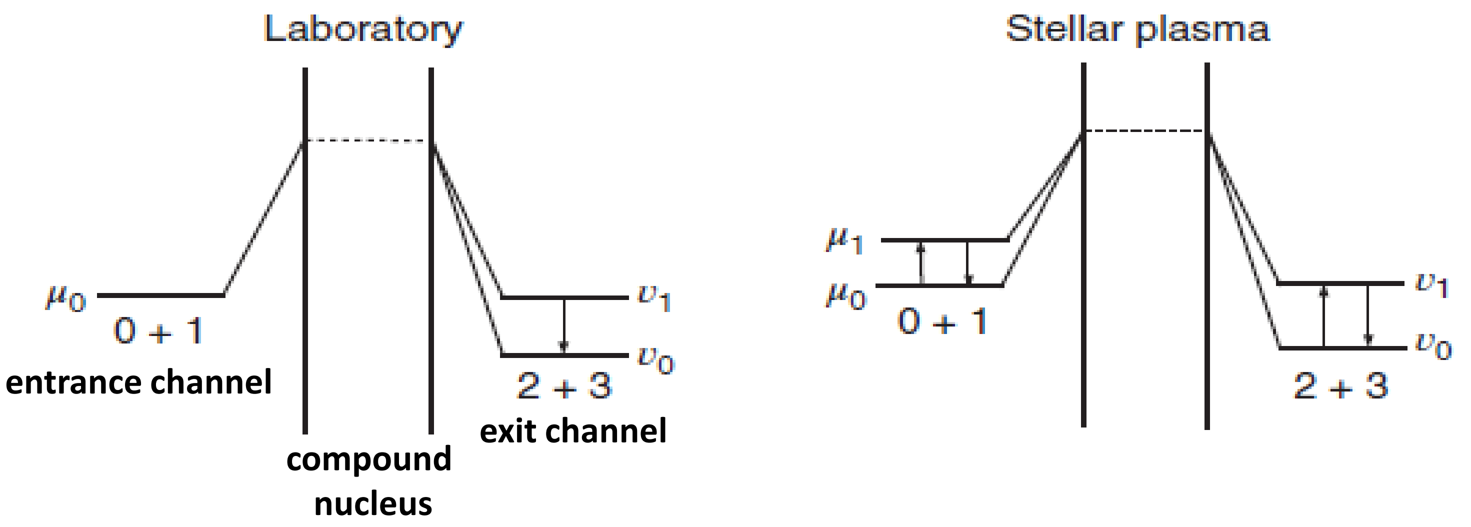
$T_{1/2} = 64.85d$

$^{90}Zr(\gamma,n)^{89}Zr$

$T_{1/2} = 78.4\ h$

This work is supported by the National Science Foundation through the Grant No. Phys - 1913258

Laboratory vs. Stellar Plasma



C. Iliadis, Nuclear Physics of Stars (2007)

The **gs contribution** to the ***stellar rate*** for photodisintegration reactions concerning *p*-nuclei typically is only a few tenths per mille.

T. Rauscher, Ap. J. Suppl. 201, 26 (2012)

Photodisintegration experiments can only be used to derive information on certain nuclear properties required for the calculation of the stellar rates and, thus, to test and support the theory (statistical Hauser-Feshbach models)!!

- **Gamma-ray strength function**
- Nuclear level density
- Nucleon-nucleus optical potential

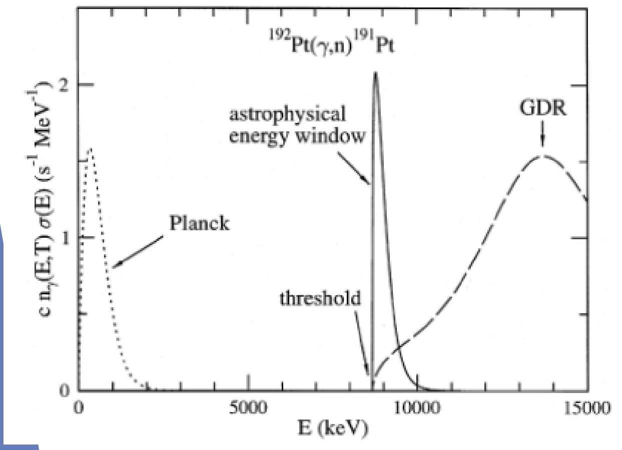
Exploring the origin of *p*-nuclei via photon-induced activation studies @ MAL

- 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

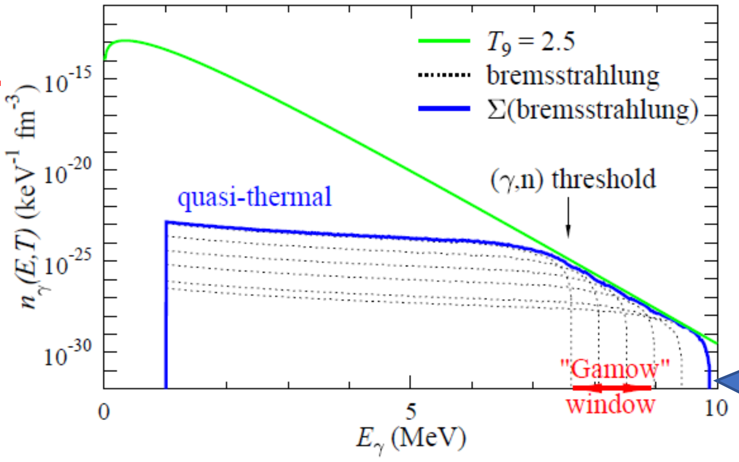
$$\lambda(T) = \int_0^\infty c n_\lambda^{Planck}(E,T)\sigma(E)dE$$

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



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

'The superposition method'



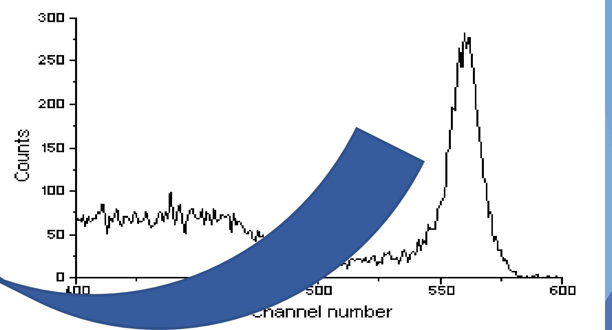
$$c n_\gamma^{Planck}(E,T) \approx \sum_i a_i(T)\Phi_\gamma^{brems}(E, E_{\max,i})$$

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

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

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

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



Determination of bremsstrahlung endpoint energy @ MAL

- Developing deuteron breakup measurements similar to ELBE facility

- Irradiate deuteron breakup target with γ and measure proton energy

$$^{2}H(\gamma, p)n$$

$$E_p[MeV] = \frac{E_\gamma - 2.22}{2}$$

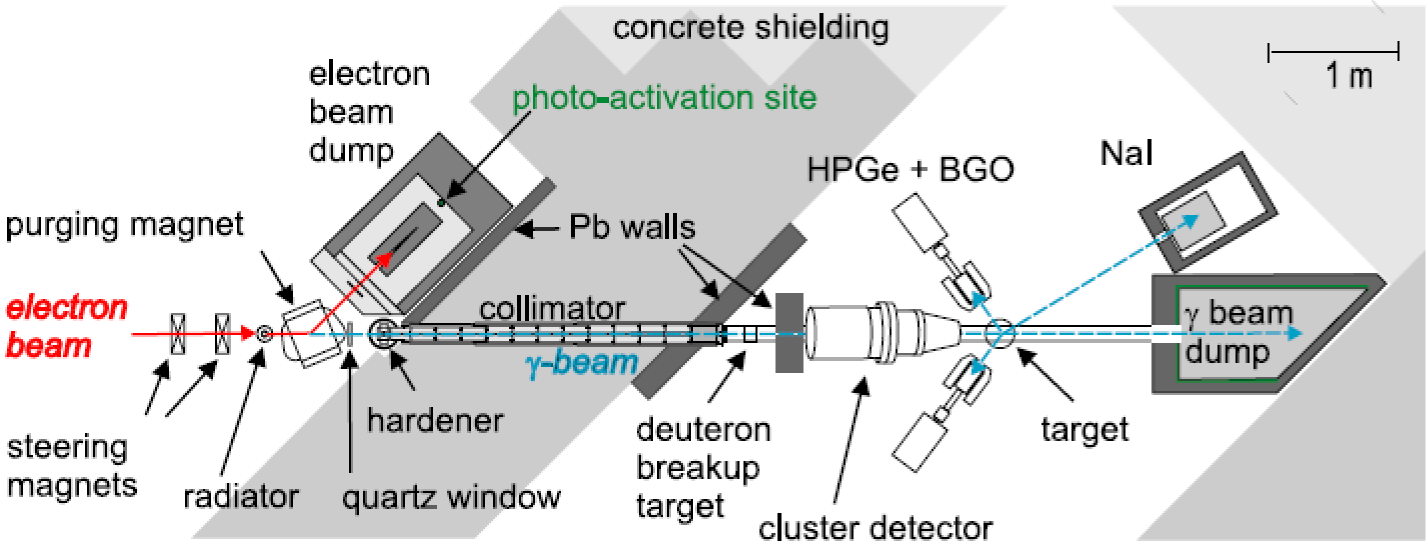
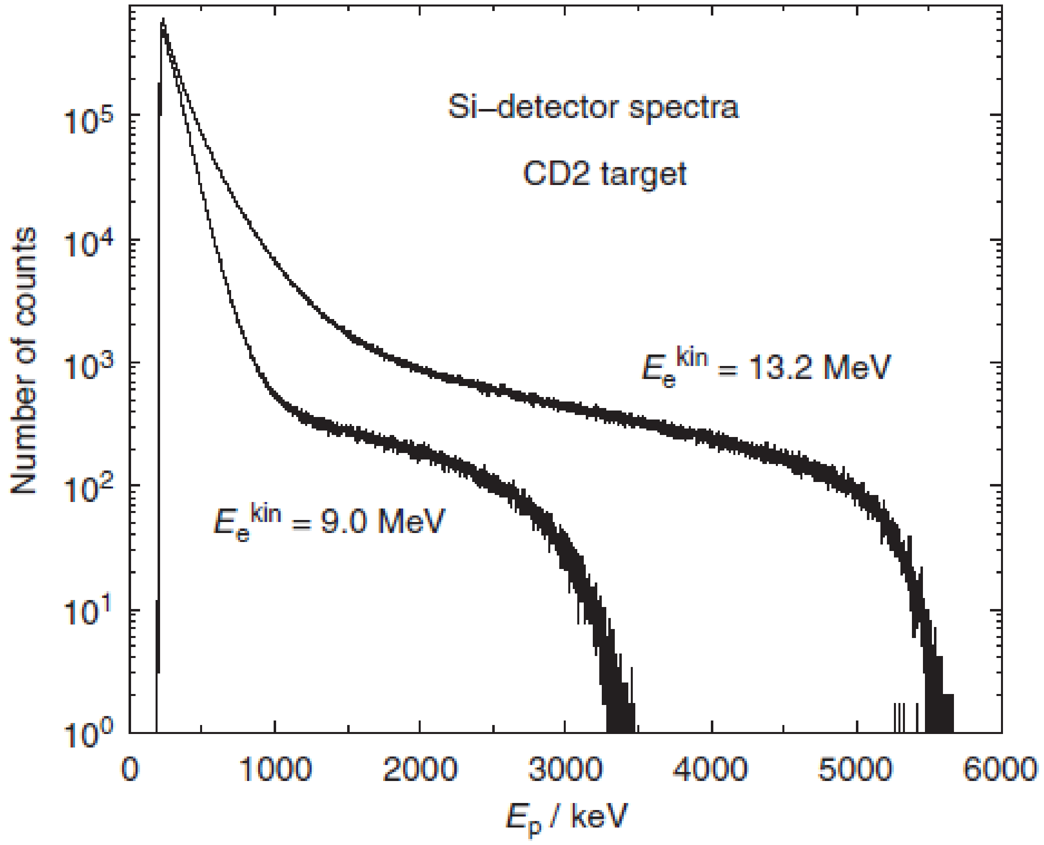


Figure 1. Bremsstrahlung facility and experimental area for photon-scattering and photo-dissociation experiments at the ELBE accelerator.

Wagner *et al*. (J. Phys. G 31 (2020))

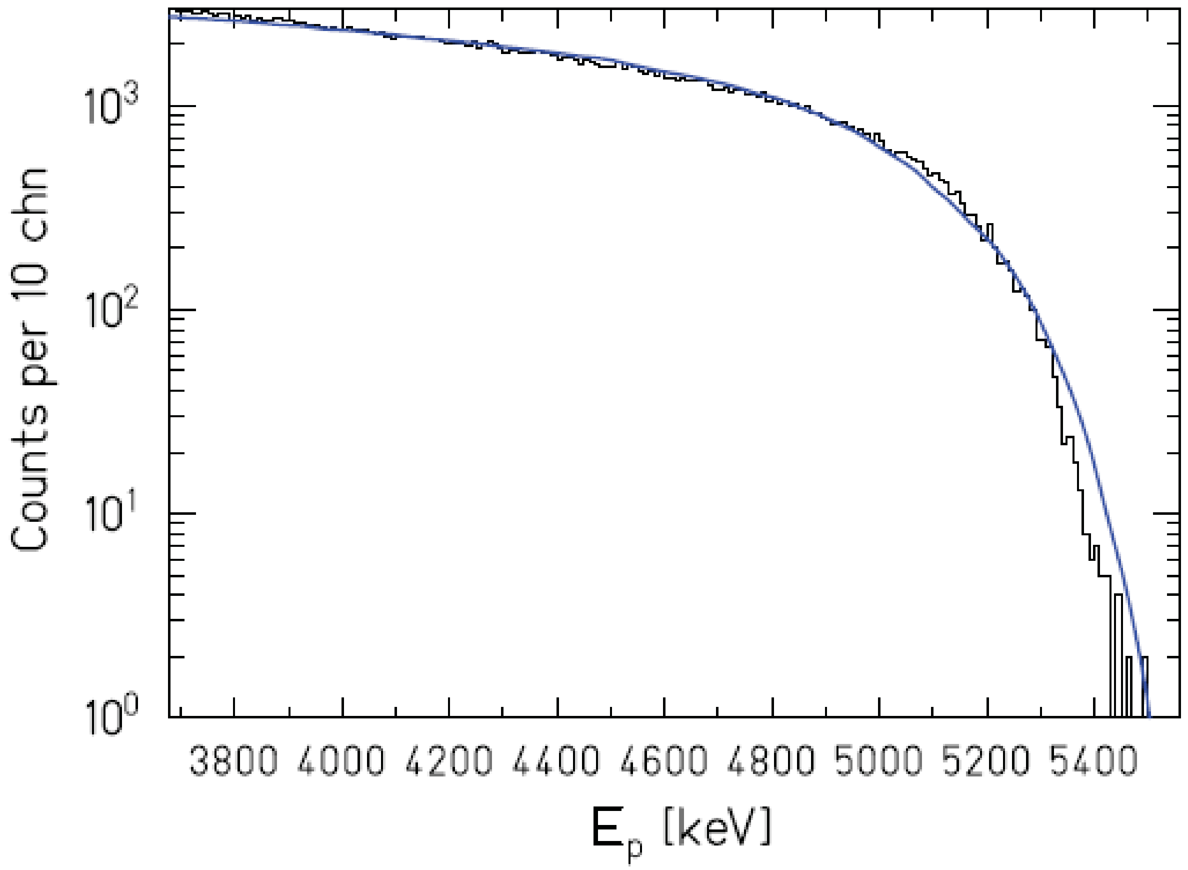
Determination of bremsstrahlung endpoint energy @ MAL (cont'd)

Photodisintegration of deuteron @ ELBE facility

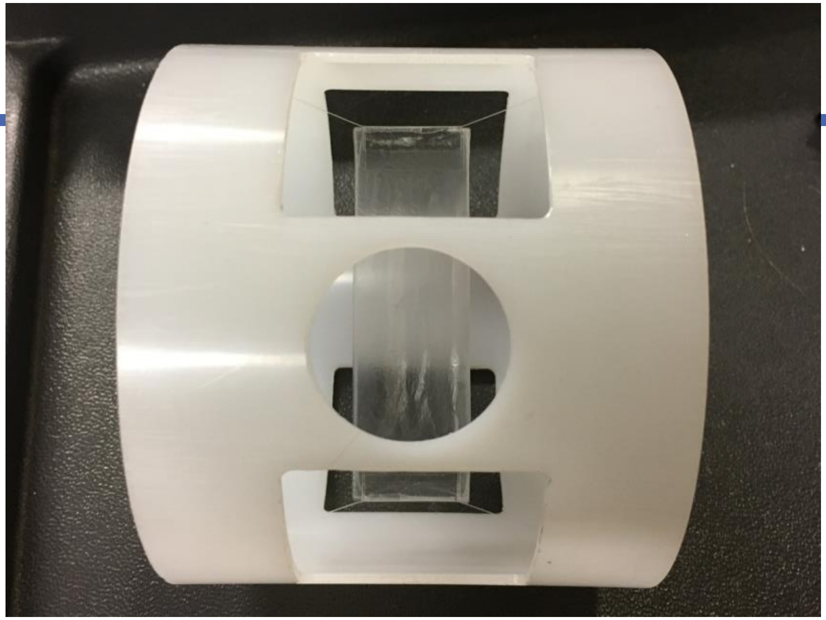


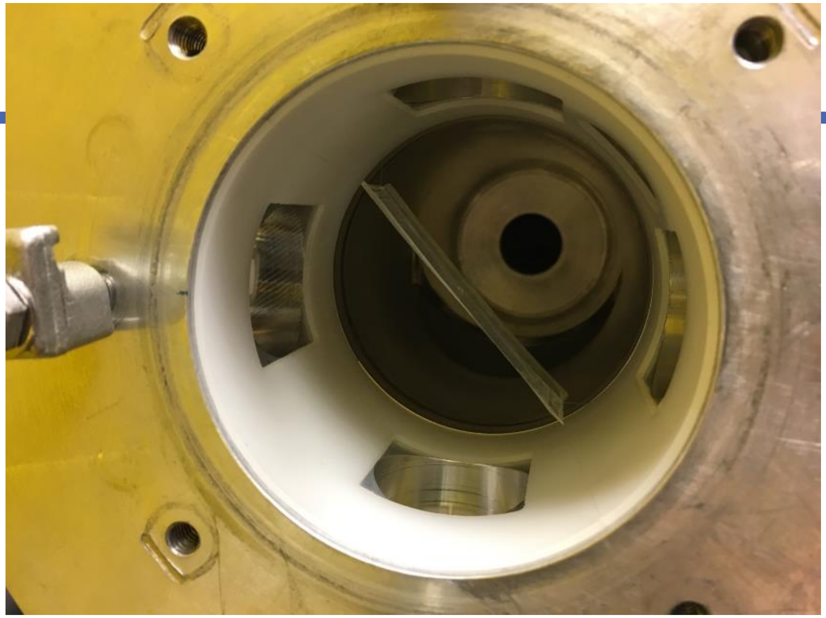
R. Schwengner et al., NIM A555 (2005) 211

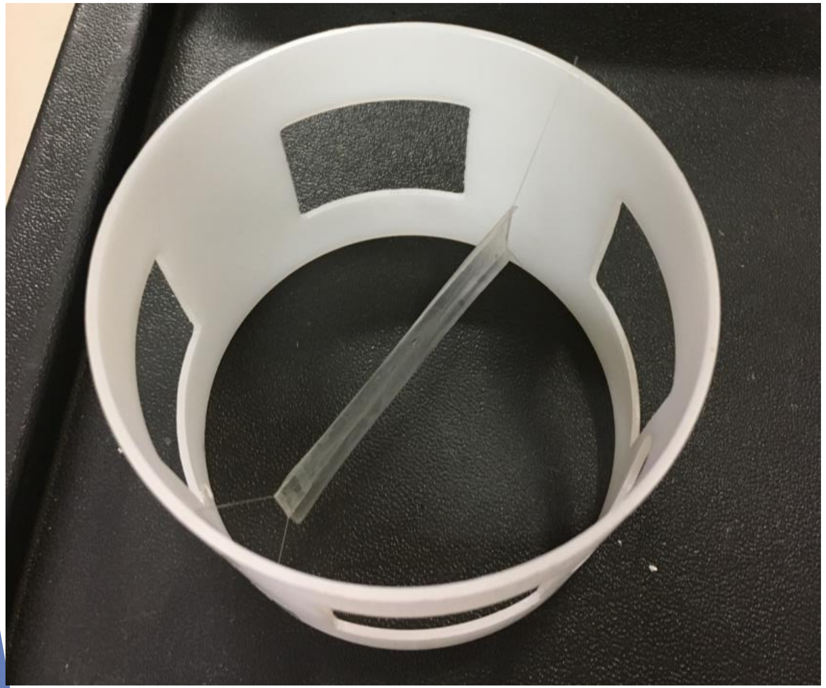
C. Nair et al., Phys. Rev. C 78, 055802 (2008)

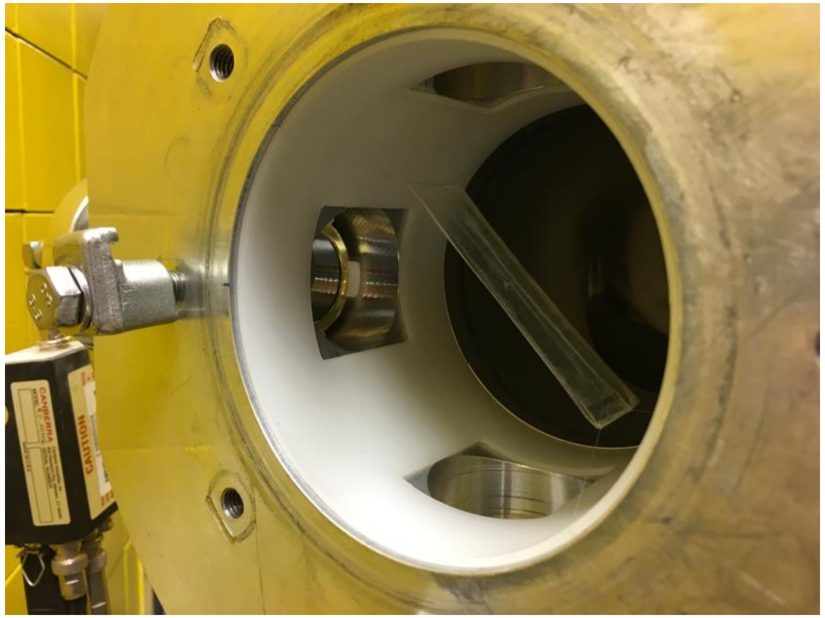


- **15 MeV @ MAL** => 6.39 MeV (max proton energy)
- **6 MeV @ MAL** => 1.9 MeV (max proton energy)









Silicon detectors

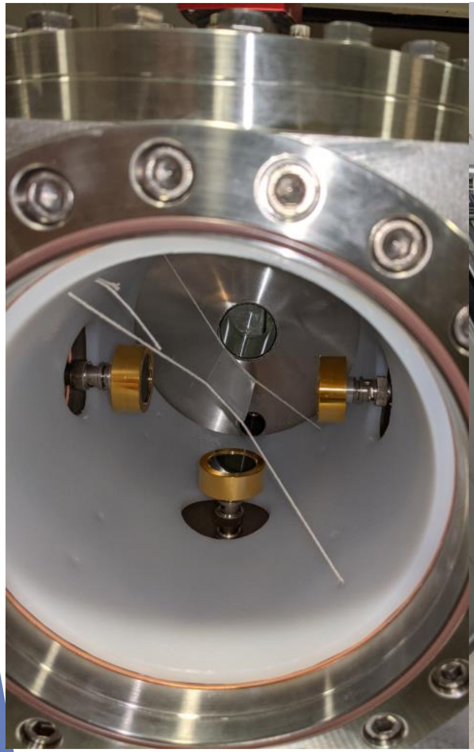
Type Ortec ULTRA
(600 mm^2, 300 μm)

ELBE.

HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

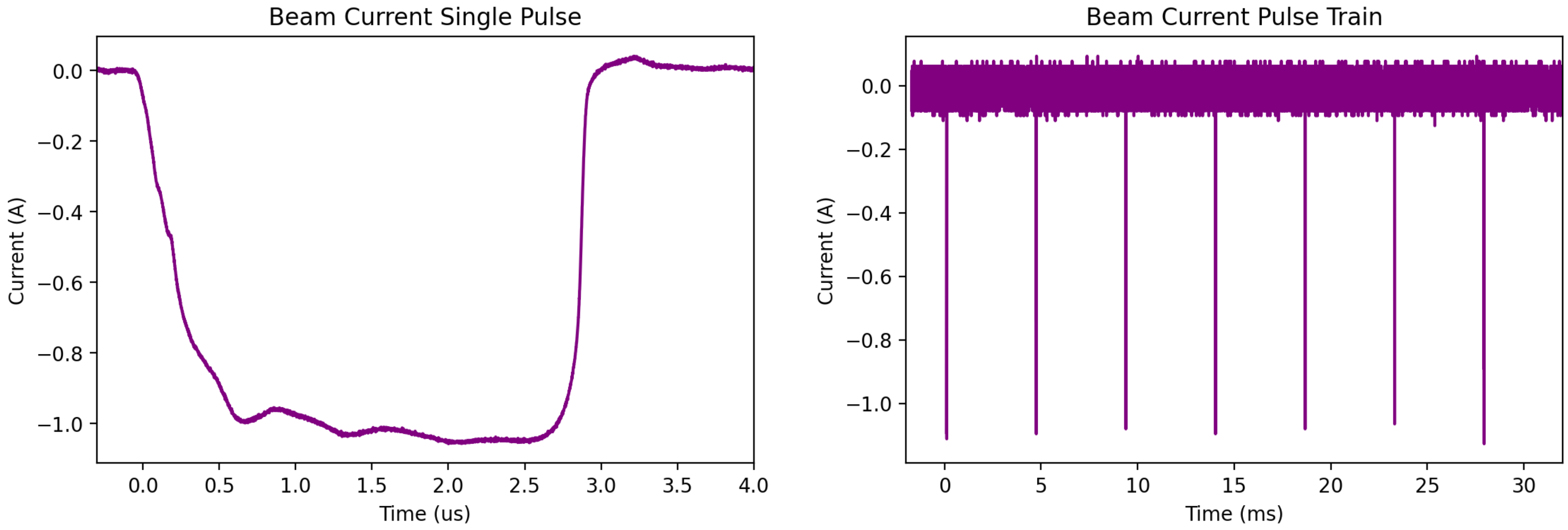
Determination of bremsstrahlung endpoint energy @ MAL (cont'd)

- Have acquired deuteron target and assembling shielded beam line



MAL electron beam time structure

- Pulsed 3 us beam at 200±10 Hz, “normal operation”



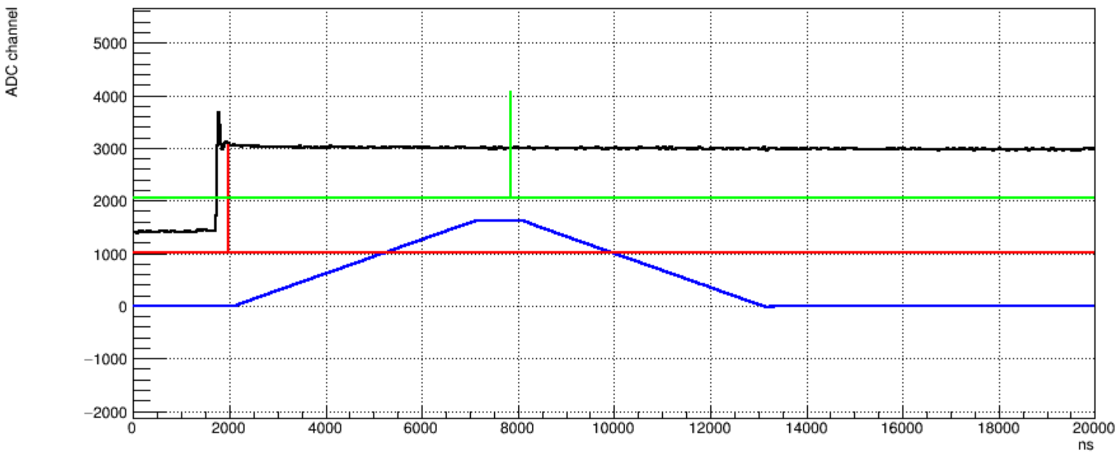
- ~0.06% duty cycle
- ~Time-averaged beam current of ~5 mA

Norfolk, Virginia
AccelApp'24

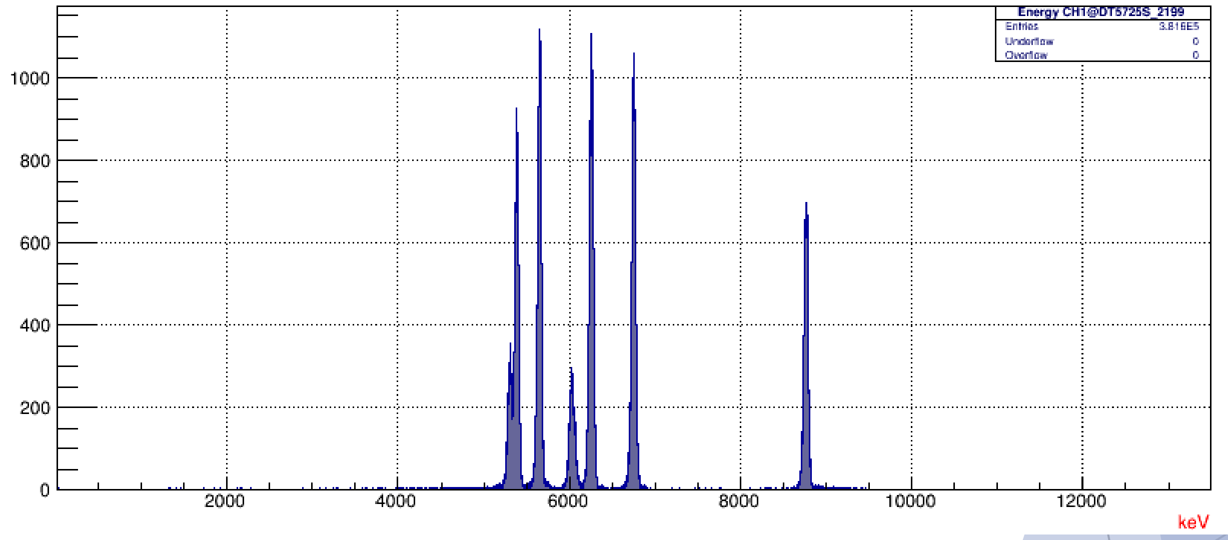
Determination of bremsstrahlung endpoint energy @ MAL (cont'd)

- Detectors installed and calibrated with slow ORTEC preamps

Normal Si Detector Pulse Count (Th-228)



Energy Calibration Spectrum (Th-228)

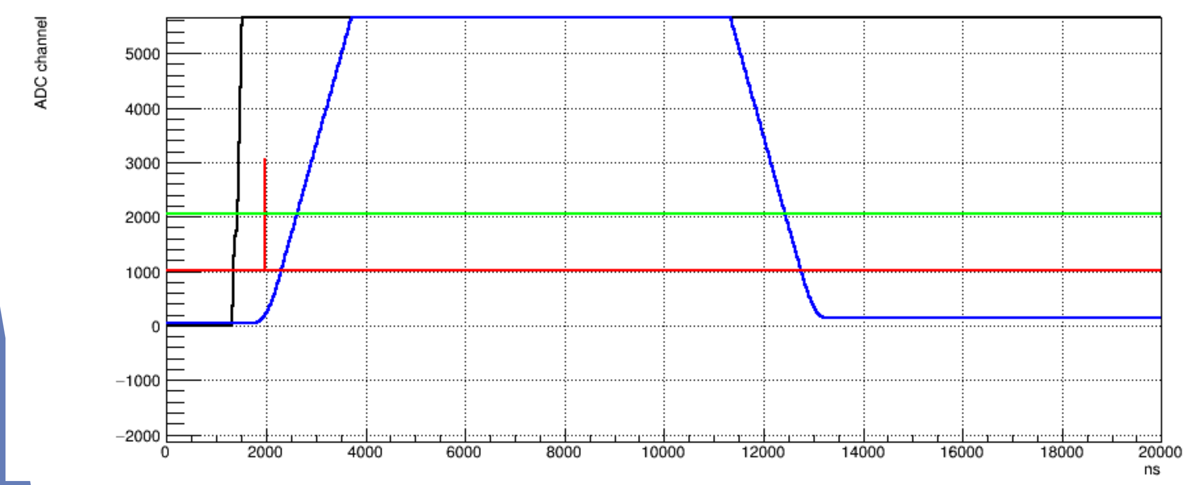


Norfolk, Virginia
AccelApp'24

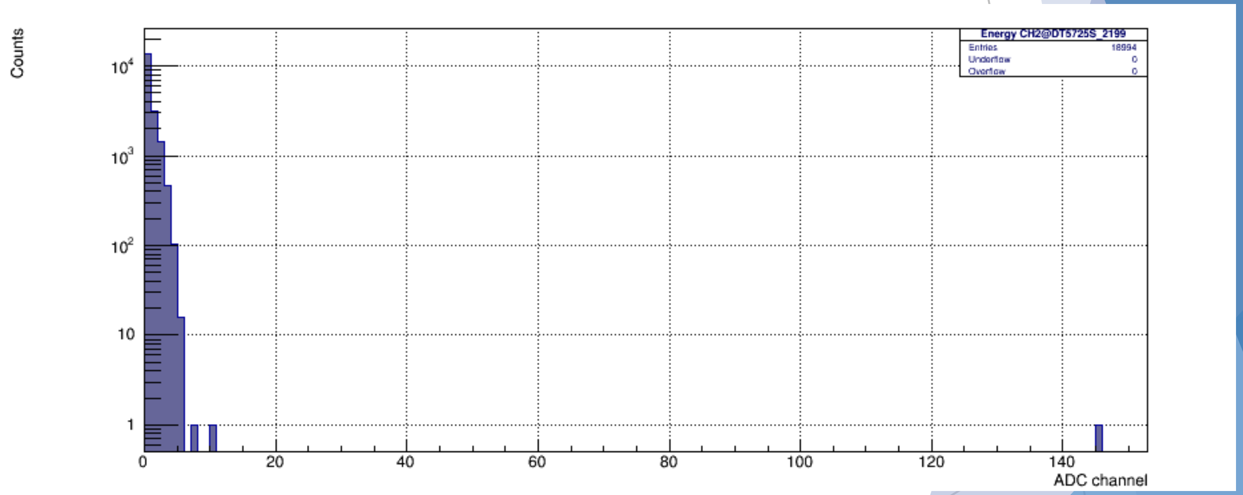
Determination of bremsstrahlung endpoint energy @ MAL (cont'd)

- Pulse structure saturates charged particle detectors
  - Average γ flux at suitable levels for detectors, but peak pulse current creates peak γ flux that saturates detectors

D-PE Scatter Pulse Count with Linac On



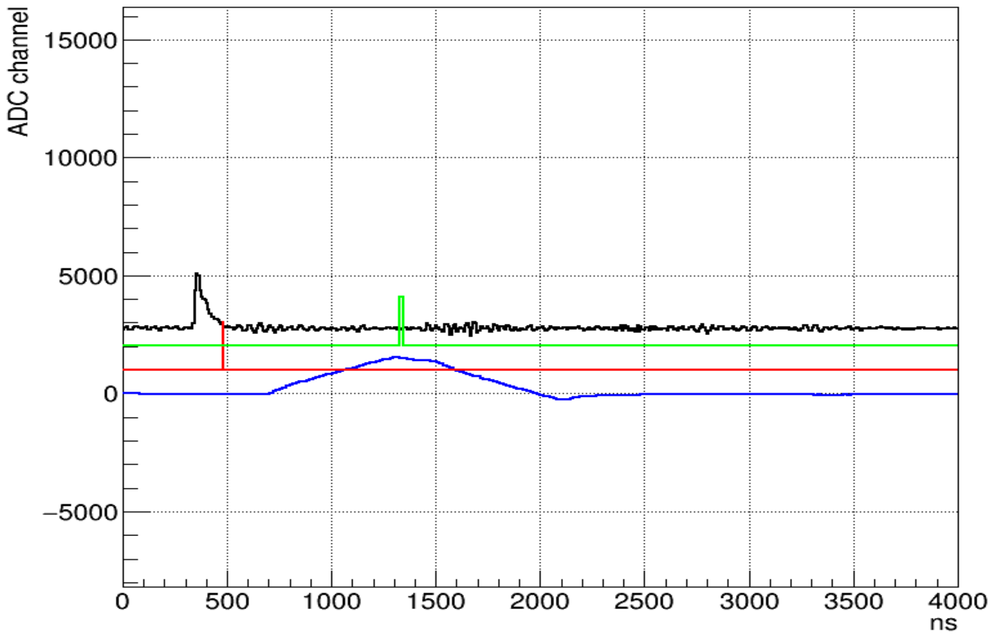
D-PE Scatter Spectrum with Linac On



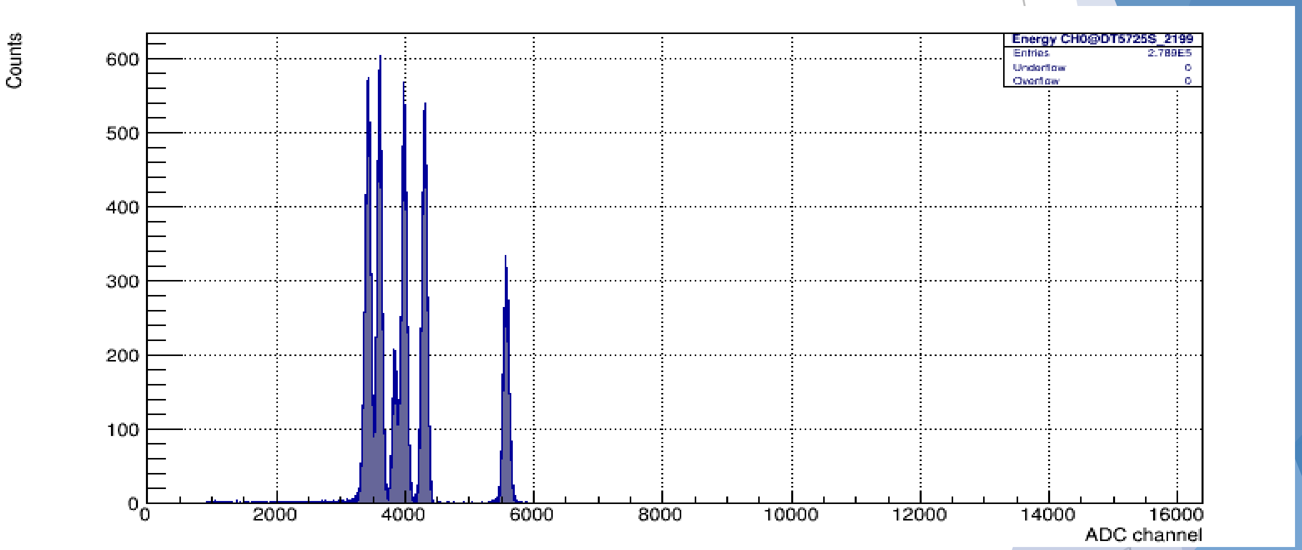
Determination of bremsstrahlung endpoint energy @ MAL (cont'd)

- Detectors installed and calibrated with new CAEN fast preamps (A1425 model)

Normal Si Detector Pulse Count (Th-228)



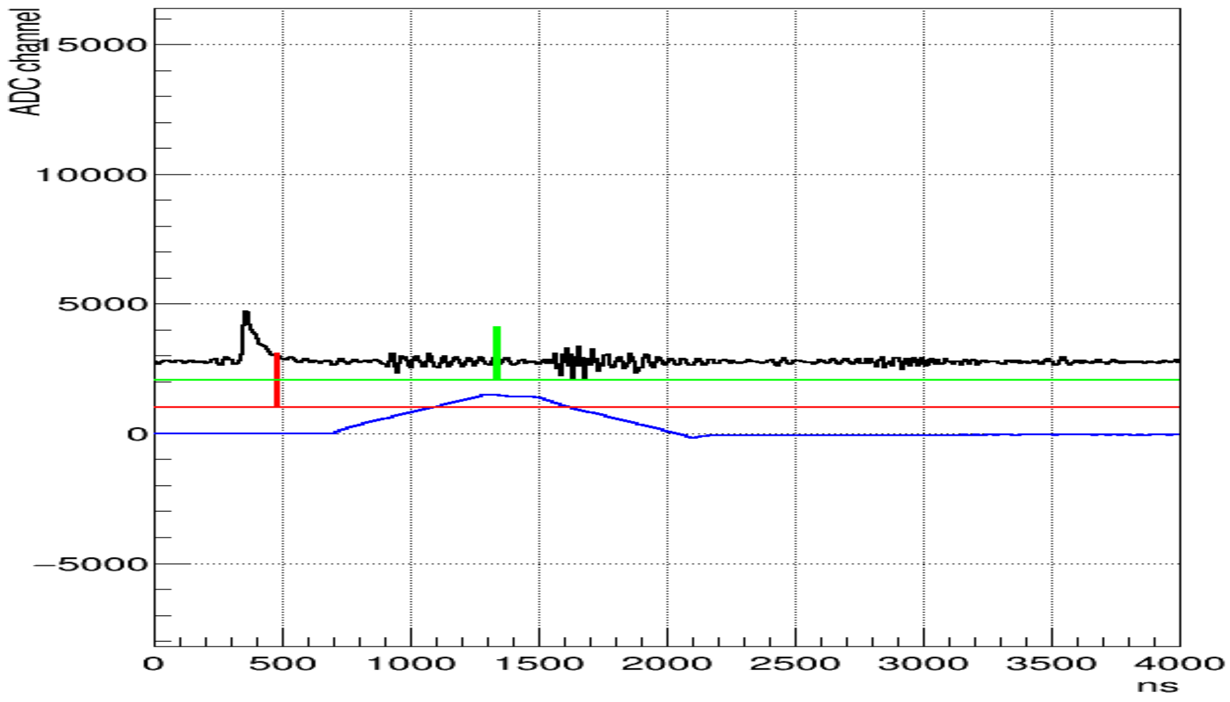
Energy Calibration Spectrum (Th-228)



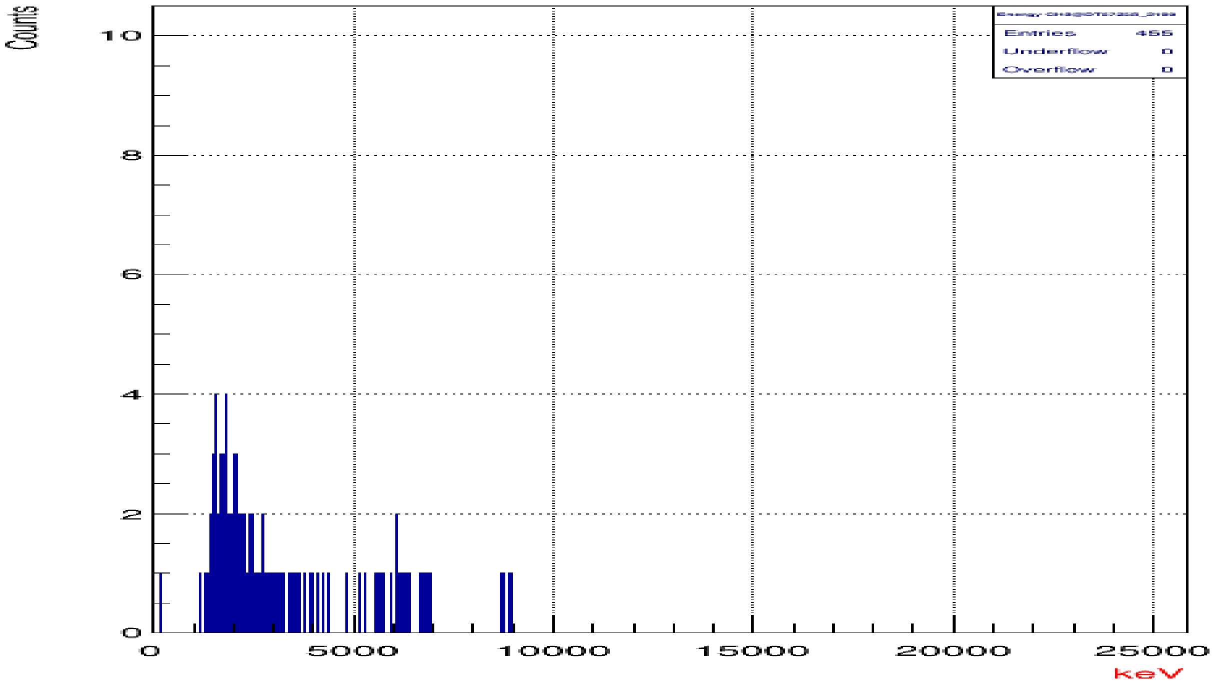
Determination of bremsstrahlung endpoint energy @ MAL (cont'd)

- Energy measurements attempted with new fast preamp

D-PE Scatter Pulse Count with Linac On



D-PE Scatter Pulse Spectrum after 10 minutes
(455 signal counts)



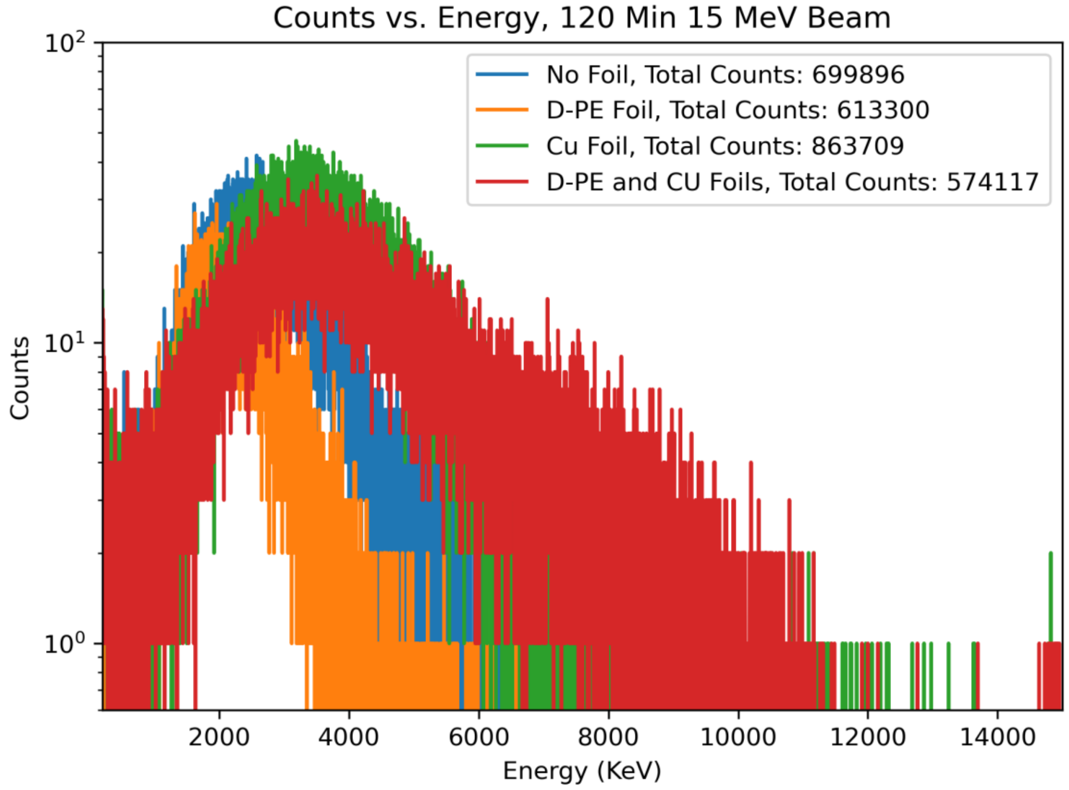
Determination of bremsstrahlung endpoint energy @ MAL (work in progress)

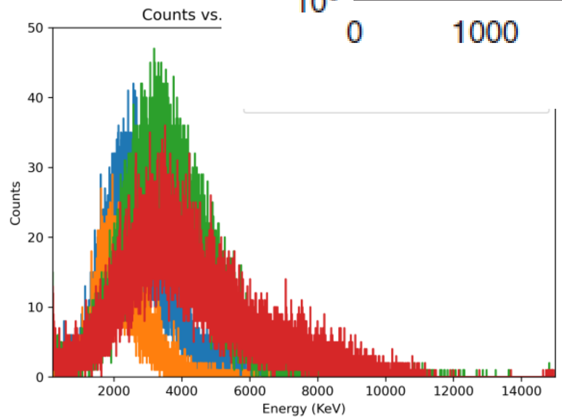
$$^{2}H(\gamma, p)n$$

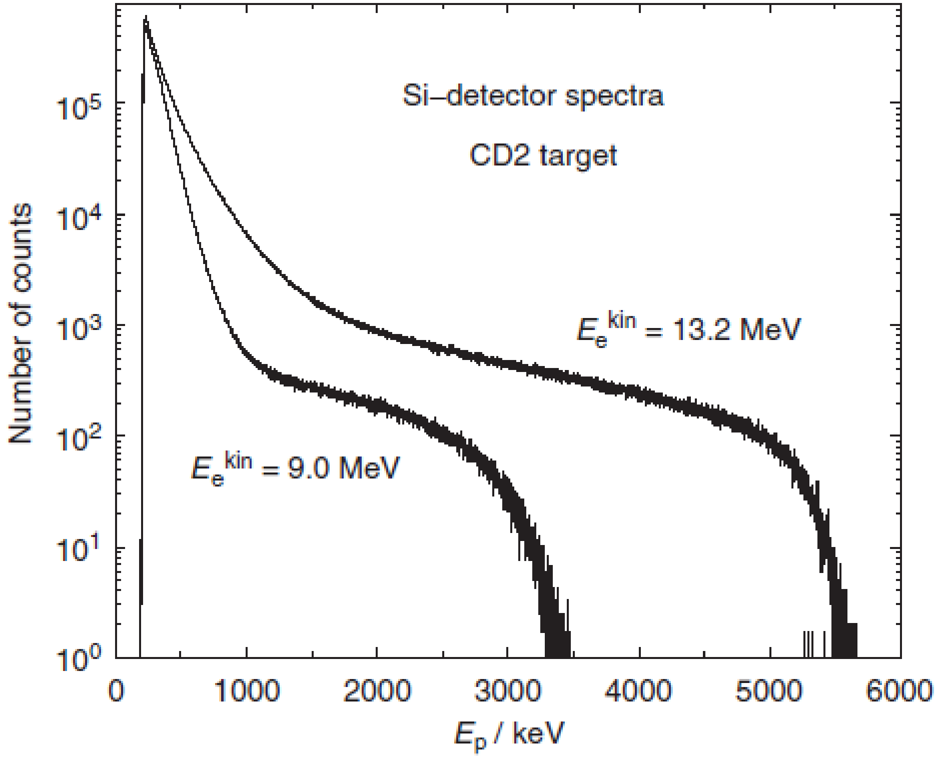
$$E_p[MeV] = \frac{E_\gamma - 2.22}{2}$$

Photodisintegration of deuteron @ ELBE facility

- **15 MeV @ MAL** => 6.39 MeV (max proton energy)







Norfolk, Virginia
AccelApp'24

Half-Life Measurements @ MAL (published results)

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

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

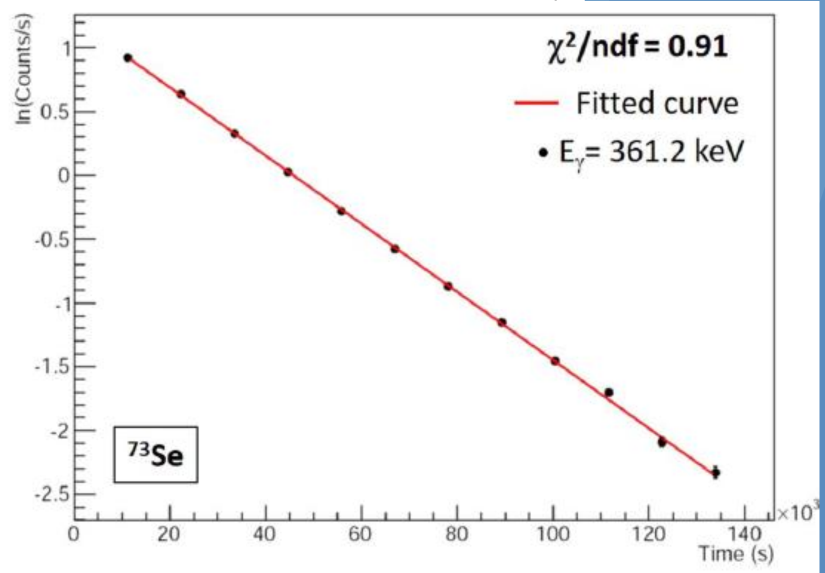
$$A_\gamma = N_T \varepsilon_\gamma I_\gamma p \frac{t_{life}}{t_{real}} \frac{\left(1-e^{-\lambda t_{irr}}\right)}{\lambda t_{irr}} e^{-\lambda t_{cool}} \left(1-e^{-\lambda t_{meas}}\right) I_{\sigma(\lambda,n)}$$

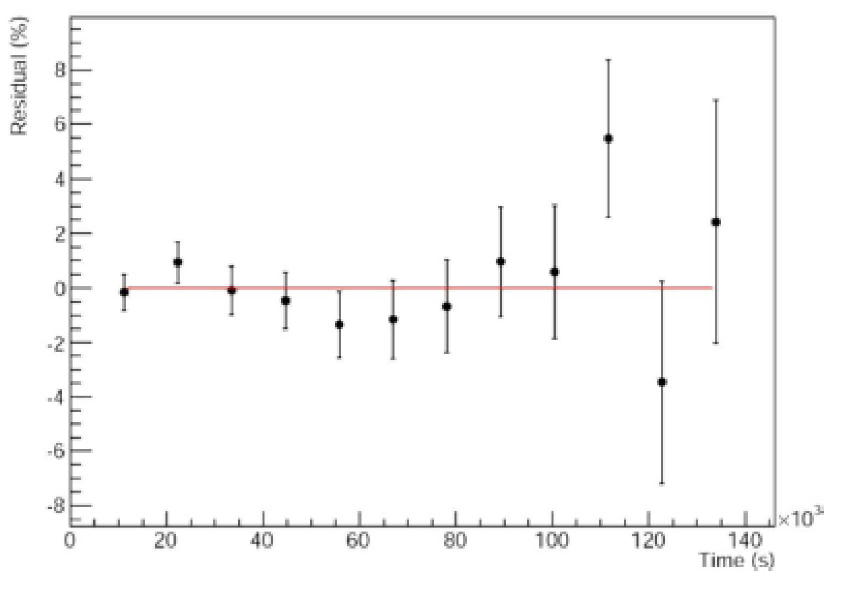
High-precision measurements of half-lives for ^{69}Ge, ^{73}Se, ^{83}Sr, ^{85m}Sr, and ^{63}Zn radionuclides relevant to the astrophysical *p*-process via photoactivation at the Madison Accelerator Laboratory

T. A. Hain[1] · S. J. Pendleton[1] · J. A. Silano[2] · A. Banu[1]

Received: 3 September 2020 / Accepted: 31 December 2020

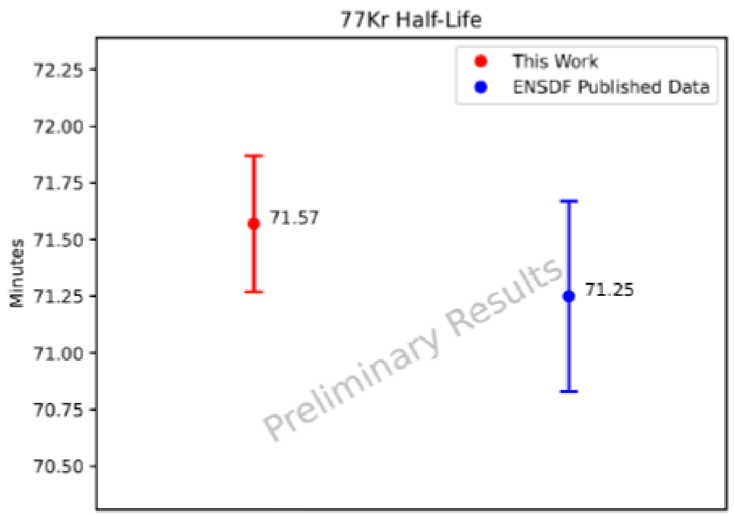
Abstract
The ground state half-lives of ^{69}Ge, ^{73}Se, ^{83}Sr, ^{63}Zn, and the half-life of the 1/2$^-$ isomer in ^{85}Sr have been measured with high precision using the photoactivation technique at an unconventional bremsstrahlung facility that features a repurposed medical electron linear accelerator. 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.

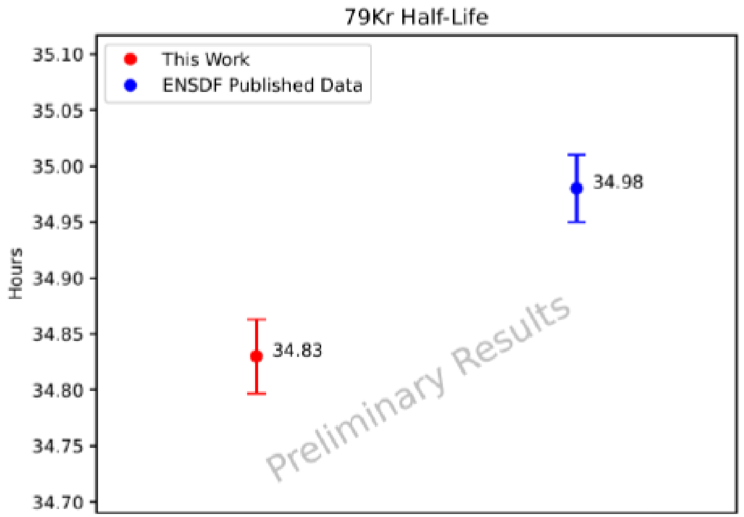


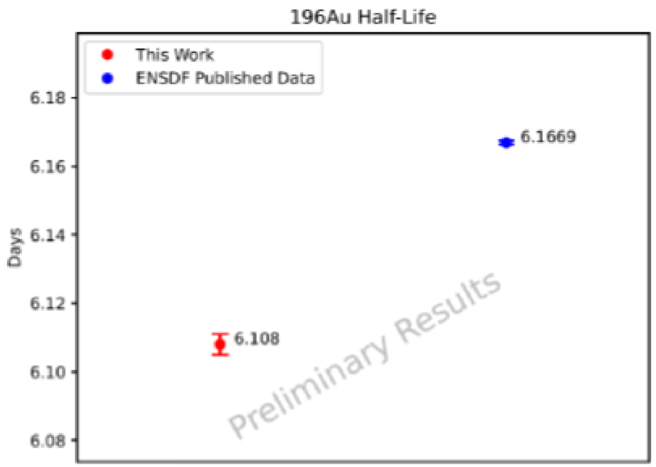


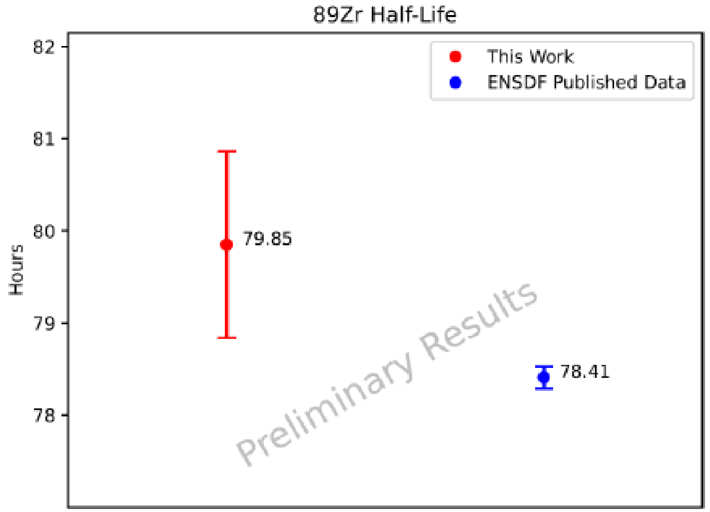
J. Radioanalytical and Nuclear Chemistry 32, 1113 (2021)

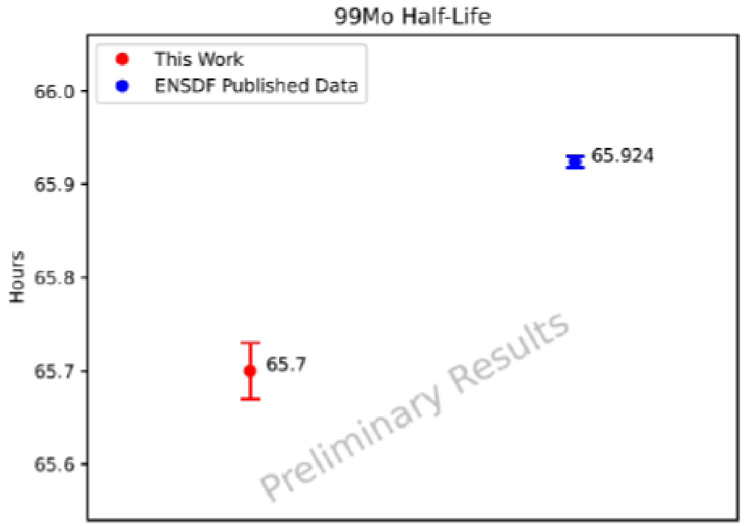
Half-Life Measurements @ MAL (preliminary results)











Acknowledgments

This work is supported by the National Science Foundation through the Grant No. Phys - 1913258

Dr. Tilda Pendleton is *Laboratory Manager at MAL* and has been contributing significantly to the ongoing development of this research project at MAL.

Robert Geissler, **Tyler Hain**, **Theodore Chu**, **Jessica Mayer**, **David Purdham**, **and Evan Witczak** are former physics major undergraduates who also contributed to this research project.

Thank you for your attention!

Norfolk, Virginia
AccelApp'24