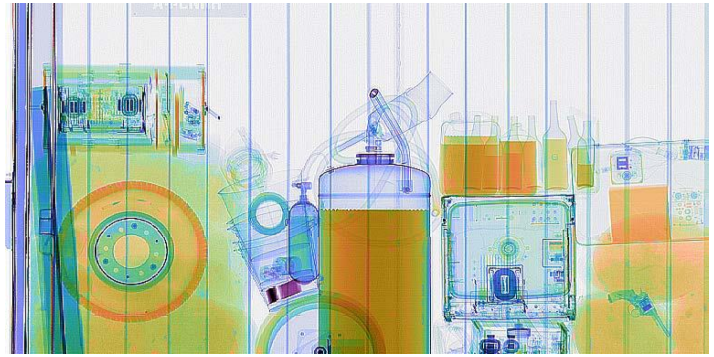
Photon Reactions and Transport

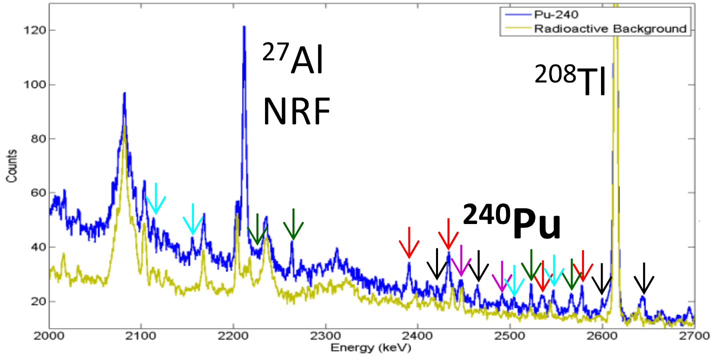
Summary Notes:

A. Homeland and Nuclear Security

Speakers: Cameron Miller (DHS), Brian Quiter (LBNL), Joseph Bendahan

- **Common aspects of the applications**
  - Photon beam interrogation of containers and materials for the purpose of identifying materials that might constitute a threat
  - Simulations of complex systems and varieties of scenarios are cost effective and necessary approaches in systems design, optimalization and scenario modeling
  - E_γ < 10 MeV to meet federal regulation
  - For transmission through thick targets, E_γ > 8 MeV
- **Data and Data Evaluation Needs (E_γ < 15 MeV)**
  - Types of data needed:
    - Photon-induced fission: prompt neutron energy spectra angular distribution, and multiplicities, prompt γ-ray multiplicities, delayed neutron and γ-ray energy spectra as a function of decay time, cumulative and independent fission yields
    - NRF cross sections
  - Validation of current photonuclear datasets
- **Transport Code Status**
  - MCNP: Relevant data libraries are mostly adequate
    - Elastic photon scattering form factors may not be correct in latest libraries
  - GEANT-4:
    - Incorrect neutron and γ-ray multiplicities for photo- and neutron-induced fission
    - Photofission model in GEANT-4 incorrect, but available tabular data is to be added in upcoming version
    - Missing NRF and photodisintegration data





First measurement of ^{240}Pu NRF

Some of these issues with GEANT-4 have been addressed with code integrations for some isotopes by, e.g., Rapiscan Laboratories, DHS and NRL

Photon Reactions and Transport

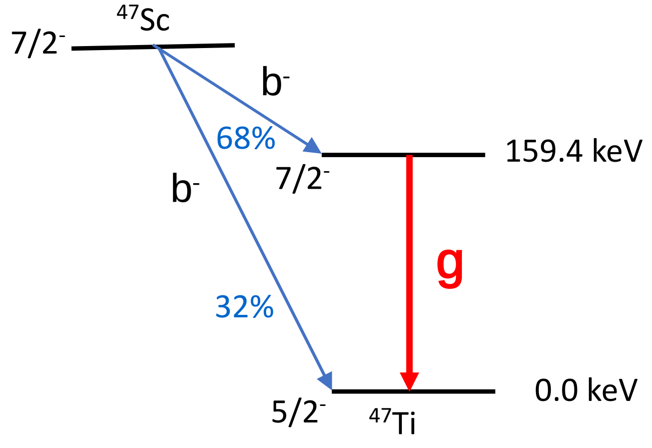
B. Medical Isotope Production via Photonuclear Reactions

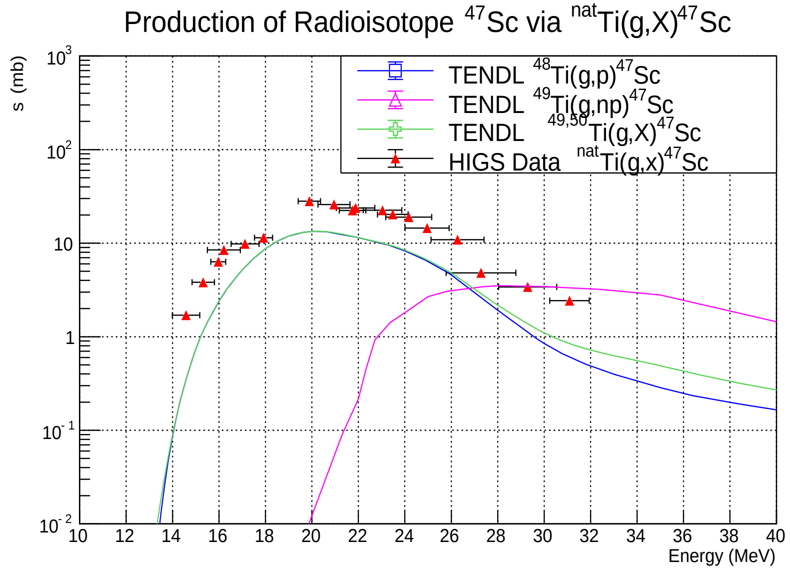
Speakers: Mohammad Ahmed (NCCU & TUNL)

- **Application**
  - Photonuclear reactions provide an option for producing radioisotopes are used for medical therapeutics and diagnostics, e.g., cancer treatment, PET imaging and SPEC imaging
  - Simulations are a cost-effective approach for designing systems for radioisotope production via photon-induced reactions. The reliability of the simulations depends on having libraries of accurate photonuclear reaction data at photon energies across the GDR region where most of the photoabsorption strength exist.
  - Recent cross-section measurements performed at HIGS on reaction pathways to the production of ^{47}Sc [^{48}Ti(γ, p) + ^{49}Ti(γ, pn) + ^{50}Ti(γ, t)], ^{67}Cu [^{68}Zn(γ, p)], and ^{195m}Pt [^{196}Pt(γ, n)].

- **Data and Data Evaluation Needs (E_γ = 1 - 40 MeV)**
  - The GEANT-4 is the standard transport code using in this application.
  - Databases used in the simulations include TENDL, JENDL, ENDF, JEFF, CENDL. The data and evaluations in these databases must be validated with experiment. Examples include (γ, n), (γ, p), (γ, 2n) and (γ, pn) reactions.
  - Cross-section measurements are needed to improve the accuracy and fill gaps in the database for photonuclear reactions relevant to producing radioisotopes important for medical treatment and diagnostics, e.g., ^{177}Lu [^{178}Hf(γ, p), ^{179}Hf(γ, pn), ^{180}Hf(γ, t), ^{181}Ta(γ, α)].

Activation γ-ray counting





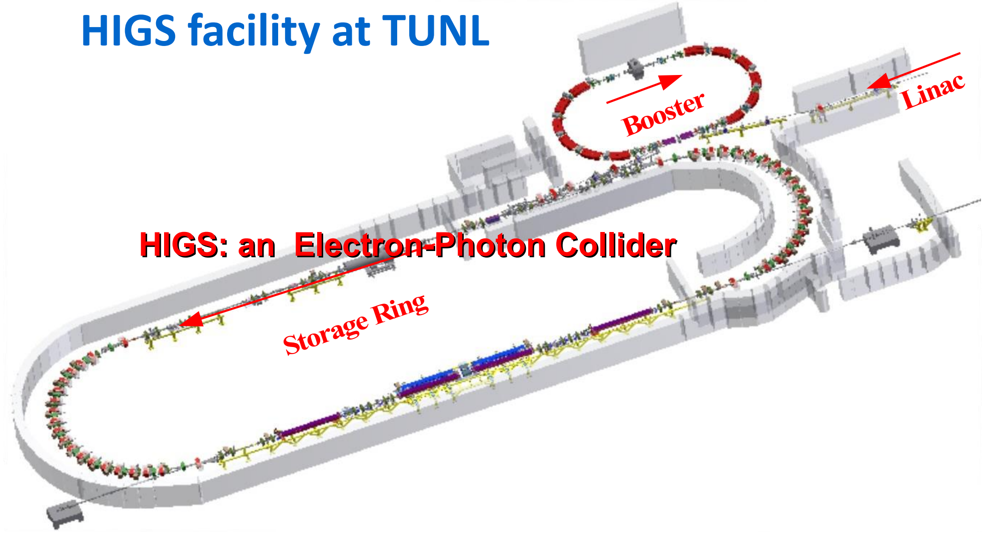
Photon Reactions and Transport

C. Photon Beam Facilities Dedicated to Nuclear Physics Research

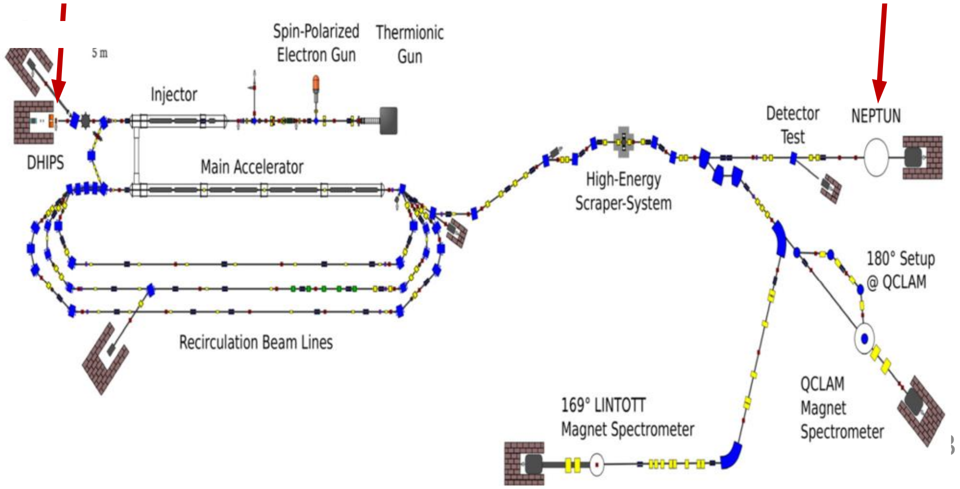
Speakers: Ying Wu (Duke University & TUNL), Norbert Pietralla (TU – Darmstadt)

- Talks were given on two classes of photon-beam facilities used in nuclear-physics research: (a) HIGS Compton source, and (b) Bremsstrahlung sources in Europe, e.g., the S-DALINAC at the TU-Darmstadt and γELBE at Rossendorf, Germany
- Bremsstrahlung and Compton photon-beam sources provide complementary beam capabilities. The broad energy spectrum provided at bremsstrahlung beam facilities enable excitation energy scans for low-spin states relative to the spin of the ground state. Compton beam sources enable high sensitivity searches for low-spin states in narrow excitation energy bands and determination of the level energy, spin and parity of excited states with high certainty via NRF measurements performed with near 100% linearly polarized photon beam.
- Recent review of photonuclear reaction technique: A. Zilges, D.L. Balabansi, J. Isaak, N. Pietralla, "*Photonuclear reactions – From basic research to applications*", Prog. Part. and Nucl. Phys. 122, 103903 (2022).

HIGS facility at TUNL



S-DALINAC at TU-Darmstadt



Photon Reactions and Transport

C. Photon Beam Facilities Dedicated to Nuclear Physics Research

Measurements enabled by facilities: HIGS, S-DALINAC at Darmstadt, and γELBE@HZDR at Rossendorf, Germany

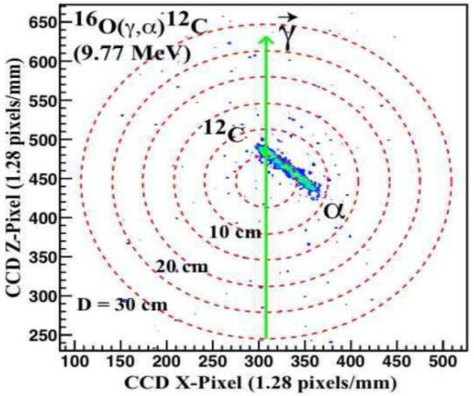
- HIGS: E_γ = 1 – 120 MeV; linear or circularly polarized beam
- S-DALINAC at Darmstadt: E_γ = 0.1 – 10.0 MeV; unpolarized beam, γELBE@HZDR at Rossendorf E_γ = 0.1 – 13.0 MeV
- NRF cross sections: broadband energy scans to search for low-spin dipole excited state, and narrow energy high sensitivity measurements with linear beam polarization for high precision determination of spin, party, and decay pattern of excited states
- Cross sections for photon-induced reactions: (γ, x) and photon-induced fissions
- Realtime particle detection techniques and activation method
- Common research areas: nuclear structure, nuclear astrophysics and photon-induced fission (fragment correlation measurements, independent and cumulative FPYs), applications (nuclear security, isotope production R&D, γ-ray detector R&D).
- HIGS research areas: Low-energy QCD: (a) Compton scattering on nucleons, and (b) photodisintegration of few-nucleon systems

$\alpha + \alpha + \alpha \rightarrow {}^{12}C + \gamma$

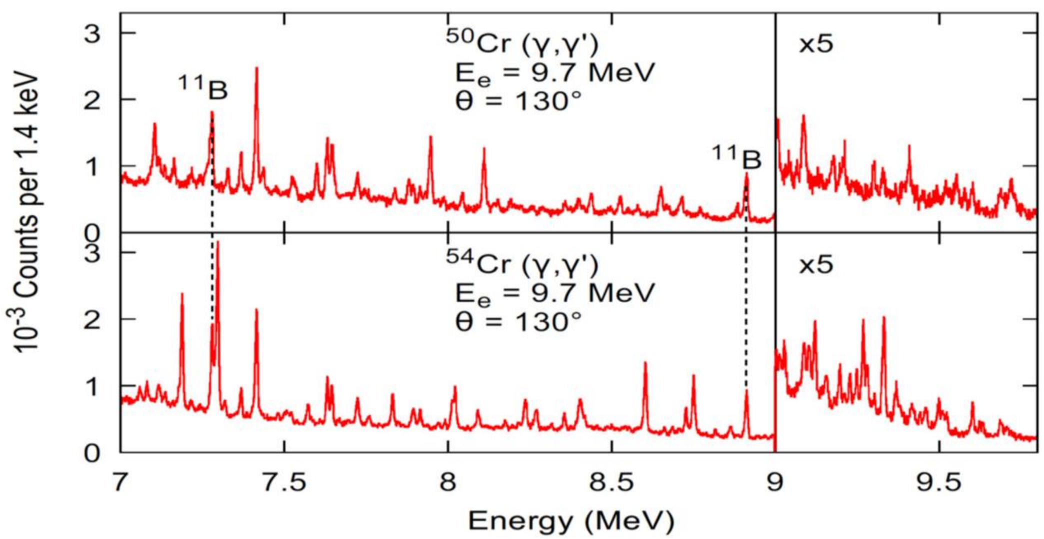
${}^{12}C$ production during helium burning

${}^{12}C + \alpha \rightarrow {}^{16}O + \gamma$

converts ${}^{12}C$ to ${}^{16}O$ => determines ${}^{12}C/{}^{16}O$



Pygmy Dipole Resonance



Photon Reactions and Transport

D. Theories for Photonuclear Reaction, and Data Library

Speakers: E. Ormand (LLNL retired) and T. Kawano (LANL)

- **Better understanding of the photo-absorption cross section**
  - Expressed by the GDR (giant dipole resonance) + QD (quasi-deuteron) models
  - GDR often represented by multiple-Lorentzians, but sometimes not enough to reproduce experimental data
  - Microscopic theory, (Q)RPA and FAM, could helpful for nuclei with no data, particularly for the light elements
  - May revisit the QD model parameterized by M.Chadwick et al. (PRC **44**, 814 (1991)) for general evaluations
  - Is R-matrix fit to light elements including photon channels possible?
- **Physics in photonuclear reaction, the same physics as neutron reactions**
  - Compound nucleus decay calculation by the Hauser-Feshbach theory
  - Gain knowledge of model ingredients, such as the level density and strength function, from neutron-induced reactions, where sufficient experimental data available
  - Pre-equilibrium decay could be improved for the photonuclear reaction case, as the current evaluations mimic neutron-induced reactions
- **Photonuclear data libraries**
  - IAEA 2019 is the most recent and updated data library, which is an international effort coordinated by IAEA
  - Evaluations based on Hauser-Feshbach model calculations
  - New experimental data from NewSUBARU included
  - Photo-fission needs more work, both theory development and experimental data, especially for the prompt and delayed neutrons and gammas, which also requires new FPY evaluations of photo-fission

Photon Reactions and Transport

E. Processing, formats and V&V

Speakers: W. Haeck (LANL) and C. Matoon (LLNL)

- **Processing**
  - Converts evaluated data into a form needed by transport codes
  - Example: log-log interpolated data to lin-lin interpolated data
  - Multigroup data for deterministic transport and continuous energy for Monte Carlo transport
- **Formats**
  - Traditional
    - ENDF-6 for evaluated data – some data types do not support covariance data
    - GENDF for multigroup
    - ACE for continuous energy (MCNP and many other Monte Carlo transport codes use this format)
  - GNDS 2.0 is a new international standard
    - Stores evaluated, multigroup and continuous energy
    - Allows for covariance data for all data types
    - New format so only limited support
- **Main ENDF-6/ACE processing code is LANL's NJOY code**
- **LLNL's FUDGE code works with GNDS**

Photon Reactions and Transport

F. Processed File Support

- **ACE**
  - Official ACE libraries for MCNP available at https://nucleardata.lanl.gov
  - Most recent photoatomic libraries are MCPLIB63 and MCPLIB84 released in 2012
  - One photonuclear library: LA150U released in 2000 (updated in 2001)
    - Limited number of nuclides
      - H2, C12, O16, Al27, Si28, Ca40, Fe56, Cu63, Ta181, W184, Pb206, Pb207 and Pb208
  - LANL plans to release a photo-nuclear ACE library based on ENDF/B-VIII.1
  - LANL has updated NJOY to better generate photonuclear ACE file and is continuing this work.
  - ACE files produced by new NJOY may only run with newer versions of MCNP
- **GNDS**
  - LLNL has processing infrastructure (FUDGE - https://github.com/LLNL/fudge) and C++ API (GIDI+ - https://github.com/LLNL/gidiplus) to support GNDS
  - FUDGE and GIDI+ handle all ENDF/B-VIII.0 photonuclear and photoatomic data
    - Except GIDI+ currently does not handle atomic relaxation data
  - A version of FUDGE and GIDI+ that supports GNDS 2.0 will be released soon
  - LLNL will release processed ENDF/B-VIII.0 data in the GNDS 2.0 format soon

Photon Reactions and Transport

G. Transport Codes: Most popular are MCNP and GEANT4

Speakers: M. Rising (LANL) and V. Ivantchenko (CERN)

- **MCNP (LANL)**
  - For photonuclear reactions, generally, uses data below ~150 MeV and physics models above that
  - Data comes from ACE files
  - Has photonuclear ACE data for 157 isotopes released to 2006
    - Photonuclear physics is off by default
    - Would like a more complete library like the neutron sub-library which has 550+ isotopes
  - Improvement to MCNP6.3 (and NJOY) have made more newer data available
- **GEANT4 (International effort)**
  - C++ toolkit available at https://geant4.web.cern.ch/
  - Implements EPICS2017 for photoatomic interactions
  - For photonuclear
    - Until recently, GEANT4 used CHIPS parameterization above 10 MeV
    - GEANT4 11.0 uses 2019 IAEA photonuclear data up to 130 MeV (per "natural isotope") and models above that energy

Photon Reactions and Transport

H. Some needs for photonuclear data

- **More Isotopes**
  - ENDF/VIII.0 has 557 isotopes in the neutron sub-library and 163 isotopes in the photonuclear sub-library
  - JENDL and TENDL have more isotopes available
    - These are not tuned to data (i.e., not evaluated but model calculated)
- **Covariance data**
  - Currently there is no photonuclear covariance data
- **V&V of data and codes**
  - Quote from Michael Rising that was echoed by others: “Validation of photonuclear data and model physics use in transport may be lacking and should be investigated”.
  - Cross code V&V would be a good first start. For example, a set of tests that the codes can model, run and compare results.