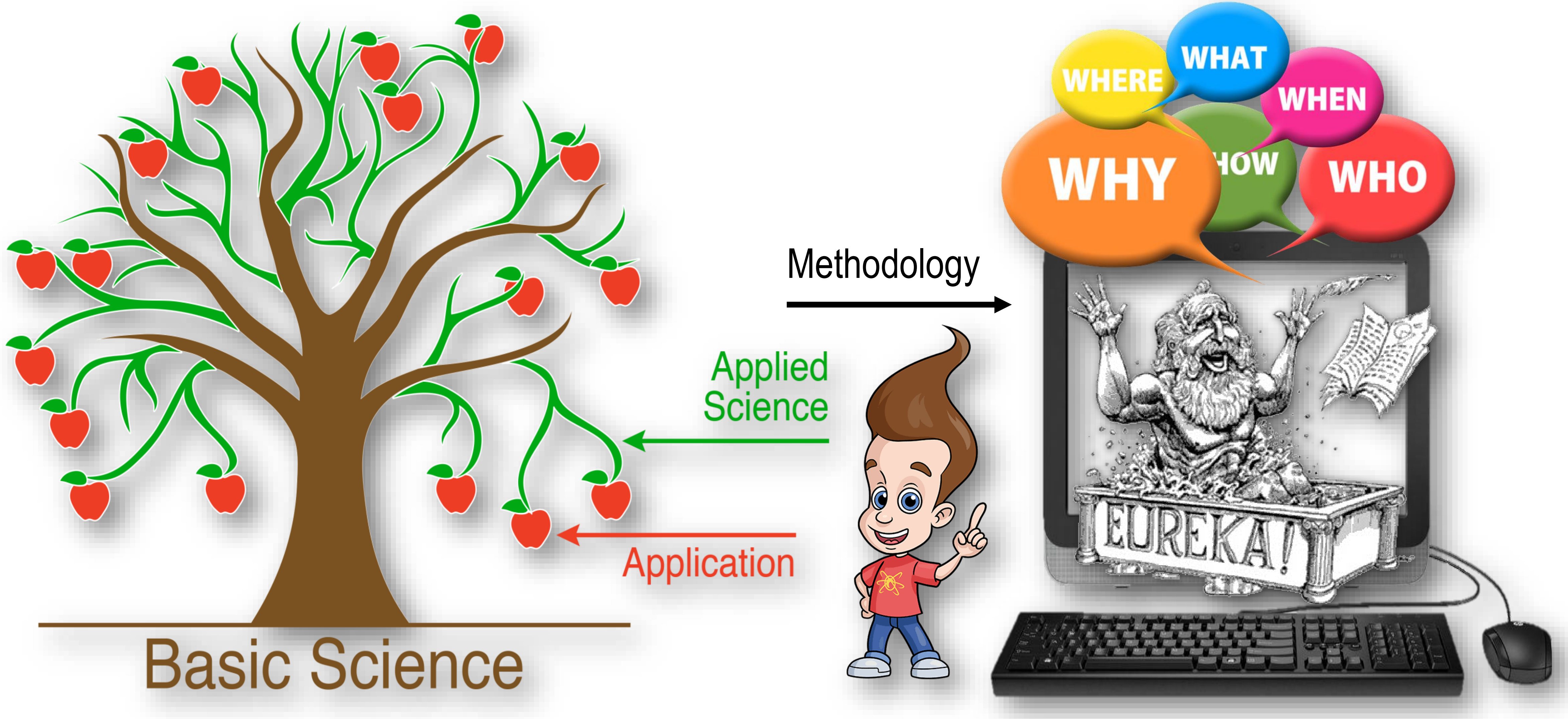

Basic Science
Applied Science
Application
Methodology
WHERE
WHAT
WHEN
WHY
WHO
EUREKA!

https://www.energy.gov/nnsa/about-nnsa

INNOVATE. COLLABORATE. DELIVER.

Nuclear Data Toward Predictive Capabilities

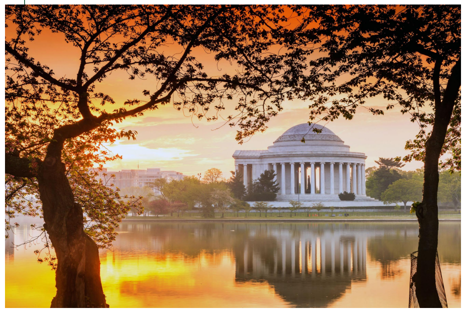
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

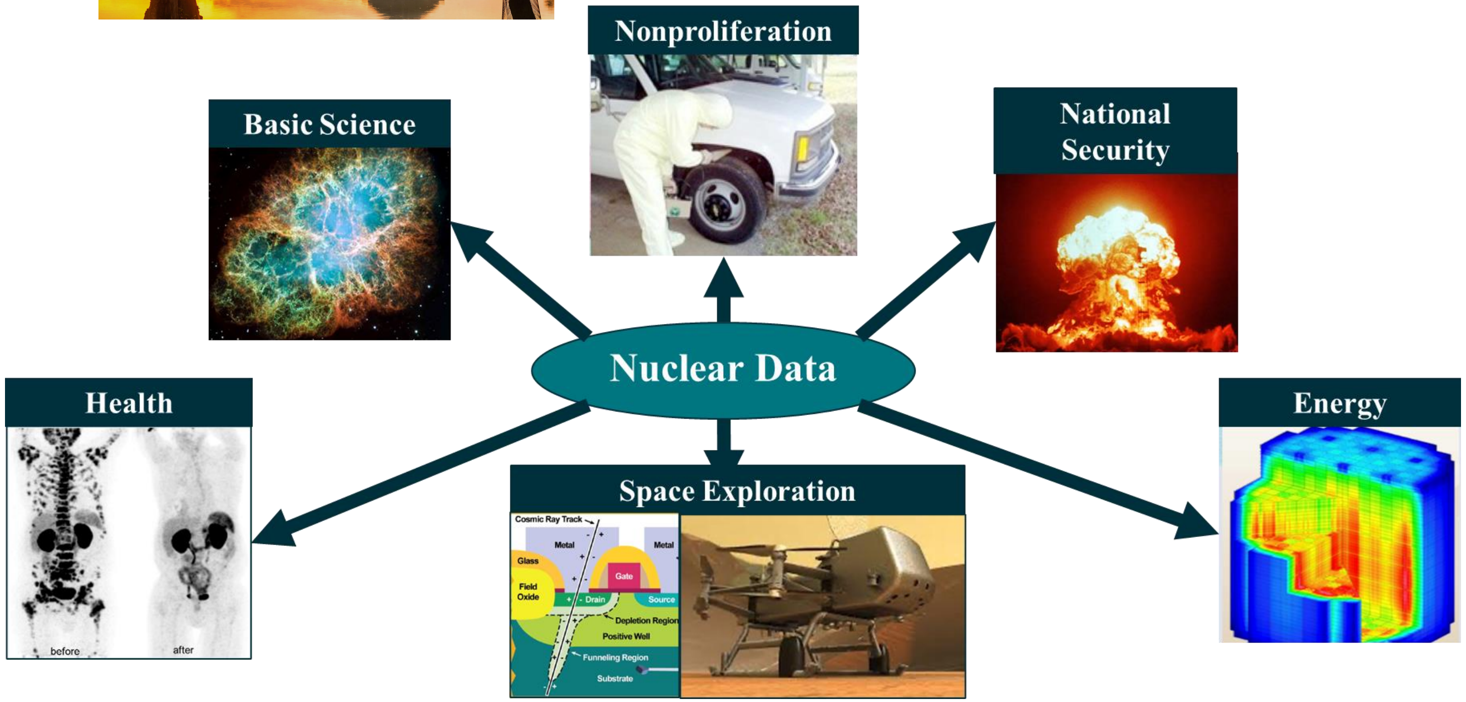
NNSA National Nuclear Security Administration

Opportunities Identified For Increased Impact/Stewardship

Workshop for Applied Nuclear Data Activities (WANDA)

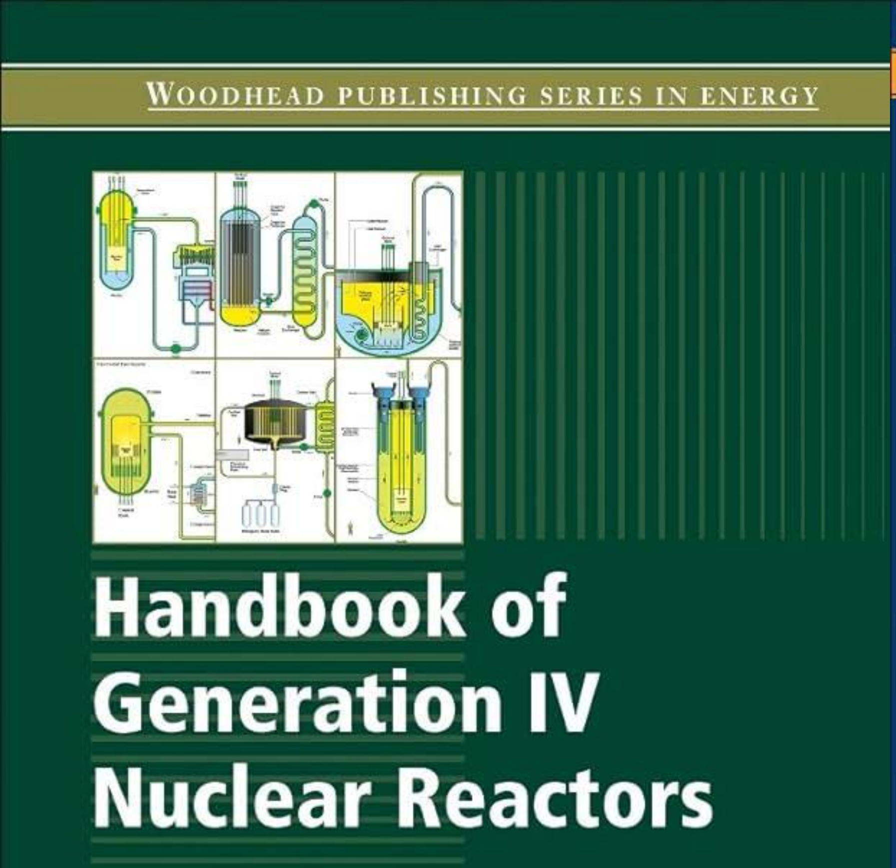


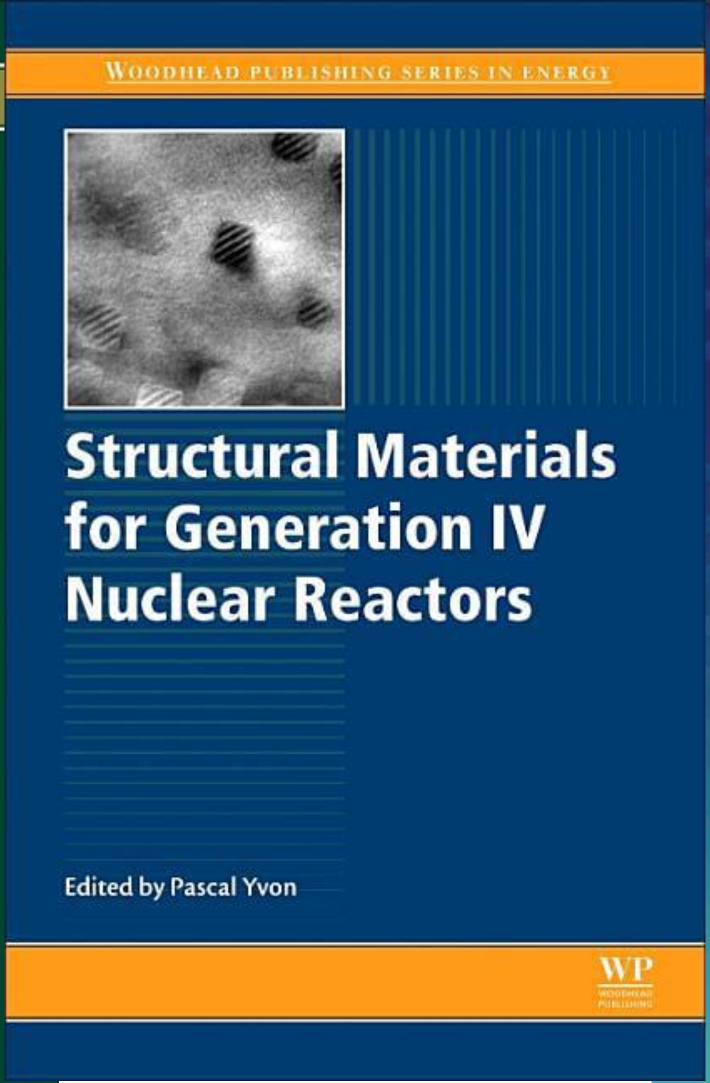
WANDA 2024
February 26th-29th

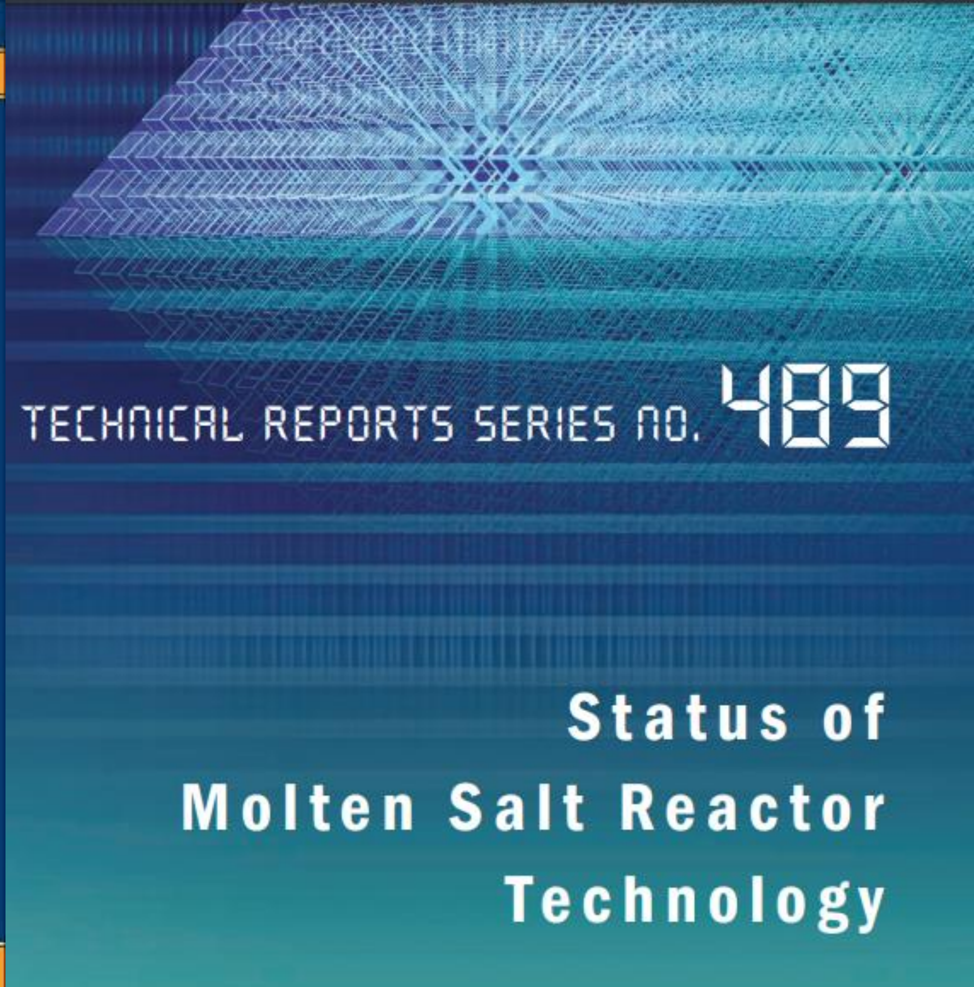


- **Cross-cutting themes** emerged that are used by many applications
  - Workforce development
  - On-going fission evaluations
  - Accelerated decay data evaluations
  - Improved reaction modeling with better links to nuclear structure
  - Neutron induced data from low- to mid-energies
  - High energy reactions and material stopping power

https://conferences.lbl.gov/event/1403/contributions/8400/attachments/4925/4626/WANDA2024.pptx







Small Modular Reactor (SMR)
High Temperature Gas-Cooled Reactor (HTGR)
Gas-Cooled Fast Reactor (GFR)
Sodium Fast Reactor (SFR)
Lead-Cooled Fast Reactor (LFR)
Fluoride-Cooled High Temperature Reactor (FHR)
Molten Salt-Fueled Reactor (MSR)

Beyond Gen IV

WP WOODHEAD PUBLISHING

Small Modular Reactors (SMR) are light water reactors that are basically advanced versions of the reactors in service today, except that they are smaller and can be mass-produced like motor cars.

The Molten Salt-Fueled Reactor (MSR) is a bit of a twofer, where the molten salt is both the coolant and the fuel. Instead of being formed into rods, pellets, or pebbles, the fuel is mixed into the fluoride salt, which flows through graphite or a similar moderator that generates slow neutrons and controls the reaction.

IAEA
International Atomic Energy Agency

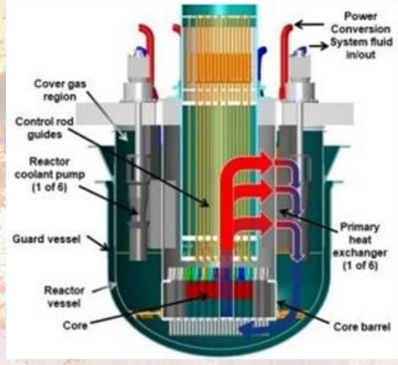
WANDA 2024

February 26th-29th

Fast Reactor Developers

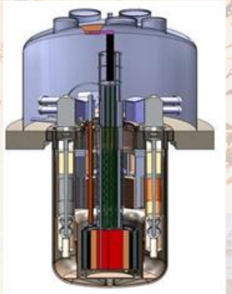
Workshop for Applied Nuclear Data Activities Sponsored by the Nuclear Data Interagency Working Group

Westinghouse



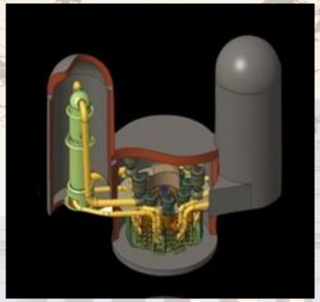
Lead Fast Reactor

TerraPower



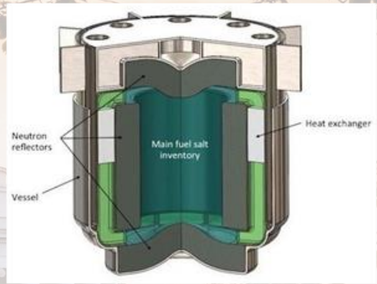
Sodium Fast Reactor

ELYSIUM INDUSTRIES INC



Molten Chloride Salt Fast Reactor

TerraPower

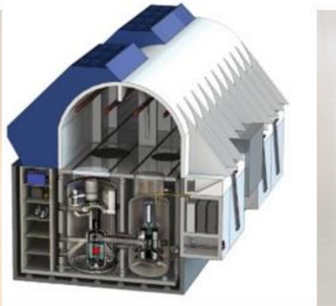


Molten Chloride Salt Fast Reactor

GE HITACHI

Sodium Fast Reactor

GENERAL ATOMICS



Gas Cooled Fast Reactor

NuGen

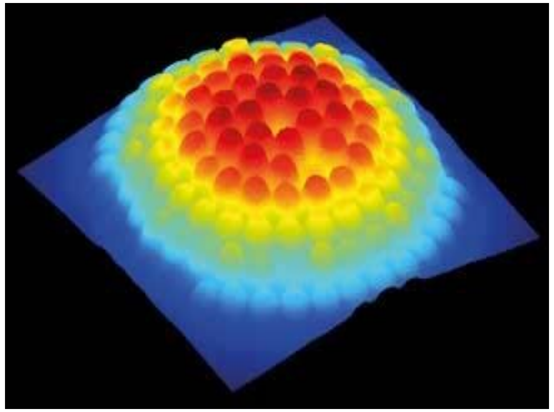
Gas Cooled Fast Reactor

Fast Reactor Cross Section Data Needs

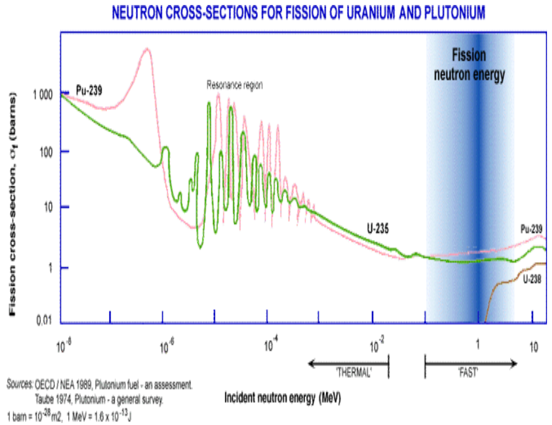
Next generation (fast reactor) reactor design is strongly dependent on modeling & simulation

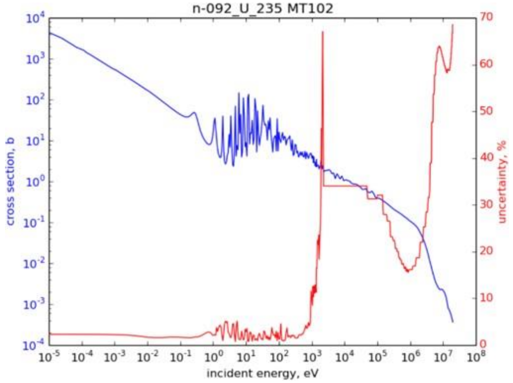
THE UNIVERSITY OF TENNESSEE KNOXVILLE

DEPARTMENT OF NUCLEAR ENGINEERING



Modeling & simulation depends on nuclear data

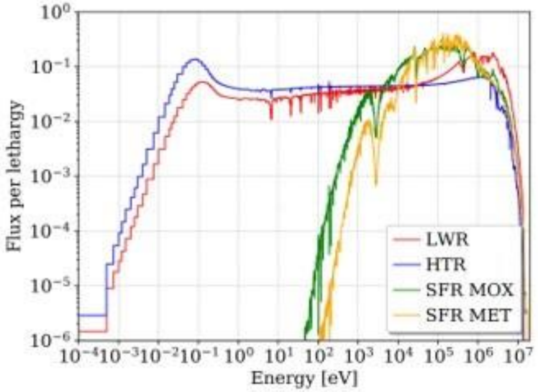




Fast Neutron Source at UTK for Cross Section Measurements in Support of Advanced Reactor Development

John Pevey, Vlad Sobes, Wes Hines jhines2@utk.edu

https://conferences.lbl.gov/event/504/contributions/4120/attachments/3090/1668/UT_Fast_Neutron_Source_WANDA.pdf



Workshop for Applied Nuclear Data Activities (WANDA 2021)

State-of-the-art Gamma-ray Spectroscopy to Enhance the ENSDF database

E.A. McCutchan, A.A. Sonzongi, S. Zhu

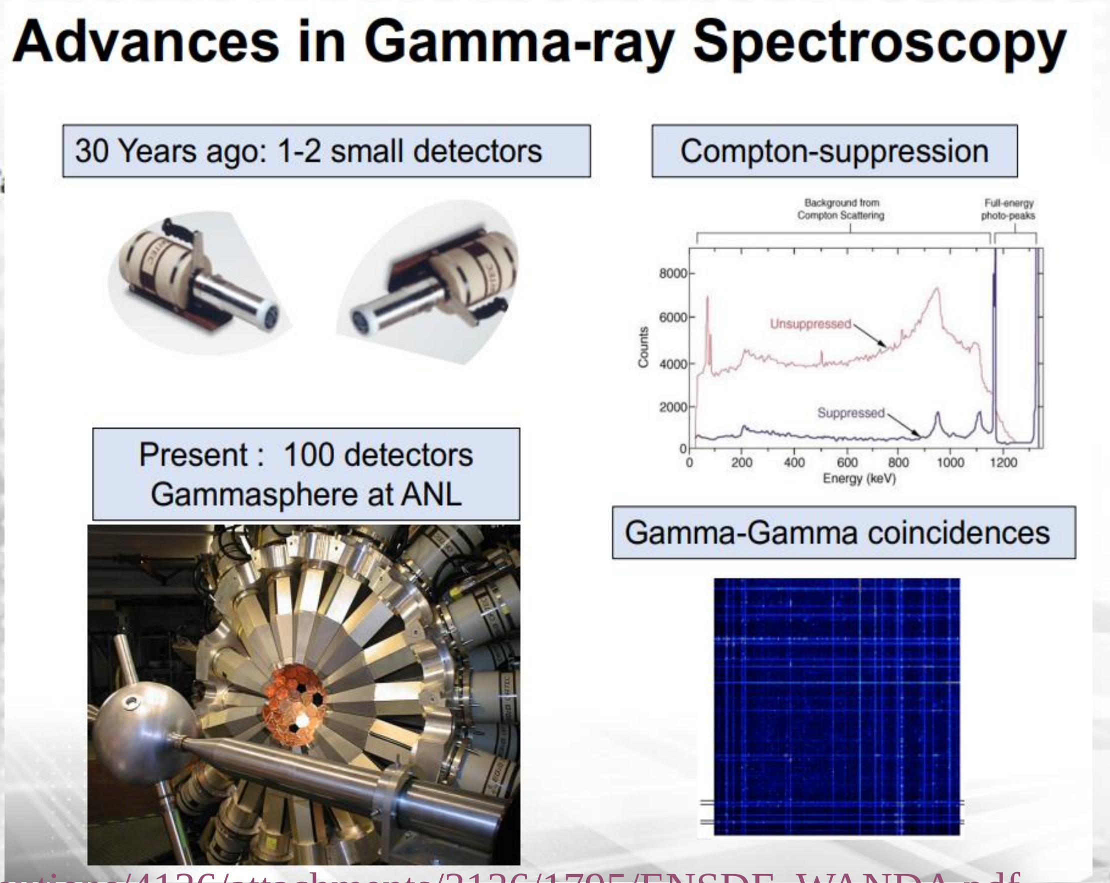
National Nuclear Data Center, Brookhaven Na

J.P. Greene, M. Gott

Argonne National Laboratory

P. Bender, P. Chowdhury

University of Massachusetts, Lowell



BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN SCIENCE ASSOCIATES

https://conferences.lbl.gov/event/504/contributions/4136/attachments/3136/1795/ENSDF_WANDA.pdf

LA METROPOLE AiX-MARSEiLLE-PROVENCE

NEA NUCLEAR ENERGY AGENCY

Wonder 2023

6th International Workshop On Nuclear Data Evaluation for Reactor applications (WONDER)

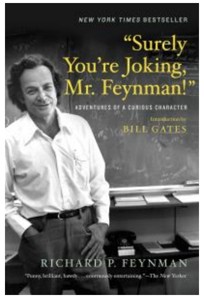
5th June – 9th June, 2023 Aix-en-Provence, France

Microscopic and integral nuclear data measurements

cea iresne

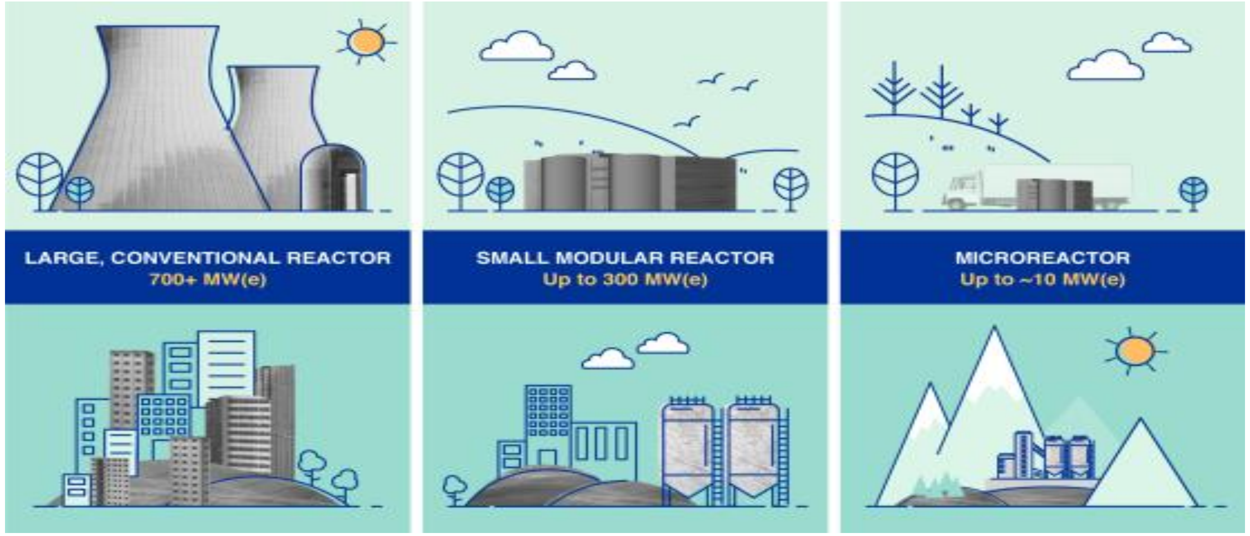
https://indico.cern.ch/event/982643/book-of-abstracts.pdf

Researching **neutron-induced reactions** is indispensable for advancing **theoretical knowledge and practical applications** across various domains, including **nuclear technology**, **medicine**, and **industry**.
Enhancing **nuclear data accuracy and precision** in **cross-section measurements** is crucial to progress in these fields.



"It doesn't make a difference how beautiful your guess is.
It doesn't make a difference how smart you are,
who made the guess, or what his name is.
If it disagrees with experiment, it's wrong."
Richard Feynman, *The Feynman Lectures on Physics*

Small modular reactors (SMRs) utilizing solid moderators have garnered attention due to their passive safety features.
One such solid moderator is calcium hydride (CaH_2)



https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

To enhance the accuracy of neutronics simulations for current and future reactor cores, a deeper understanding of neutron behavior is crucial. Neutron population dynamics, driven by reactions like **(n, xn) and inelastic scattering**, significantly influence core performance.

Despite their importance, precise cross sections for these reactions remain elusive. One approach to determine this cross section involves employing **prompt γ-ray spectroscopy alongside time-of-flight measurements**.

However, **incomplete knowledge of isotope's level scheme poses challenges**, with discrete states assumed known only up to 1.3 MeV and uncertainties in branching ratios. Sensitivity analyses using the **TALYS code** can substantially impact **(n, n'γ)** cross sections.

Neutron Scattering Cross Sections: (n,n'), (n,γ), (n, n'γ)

Nuclear data, encompassing neutron scattering and attenuation cross sections, along with γ-ray production rates, play a pivotal role across diverse technical domains:

Basic Nuclear Science: Fundamental research and understanding of nuclear processes.

Experimental Design and Analysis: Essential for designing experiments and analyzing results accurately.

Medical Treatment and Dosimetry: Vital for radiation therapy planning and dose calculations in medical settings.

Fission and Fusion Power Industries: Crucial for reactor design, safety, and optimization in nuclear power generation.

Homeland Security: Critical for detection and mitigation of nuclear threats, ensuring national security.

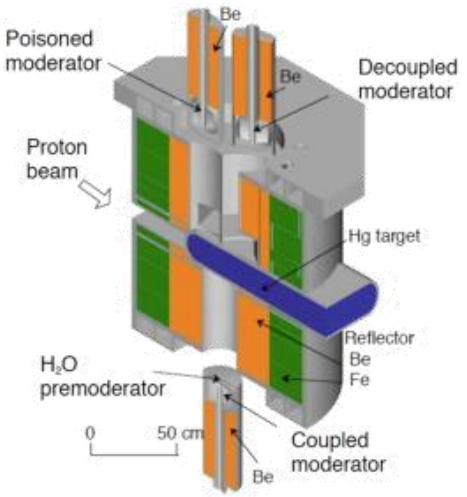
Non-Proliferation and Safeguards: Key for monitoring and verifying compliance with nuclear agreements and treaties.

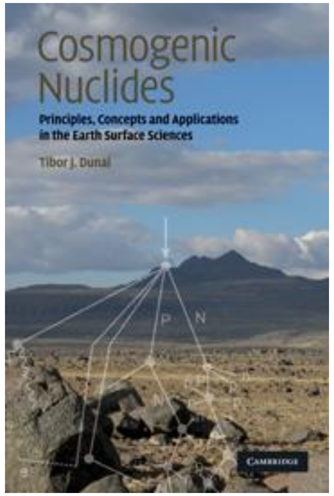
Interrogation Communities: Utilized in various interrogation techniques and technologies.

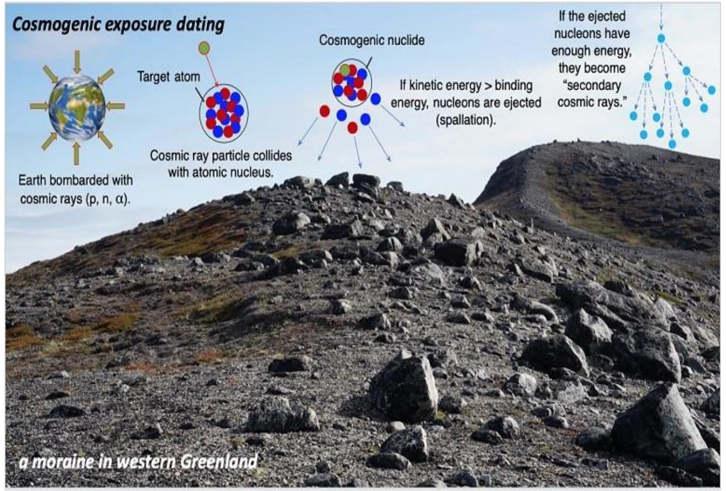
Nuclear data underpin advancements and applications across a spectrum of fields, driving innovation and safety in numerous technical endeavors.

Which of ^{9}**Be**, ^{40}Ca, or ^{75}As would be more suitable for presenting at the ISINN-30, considering its significance in nuclear, natural, life, and environmental sciences, as well as their potential impact on human society?

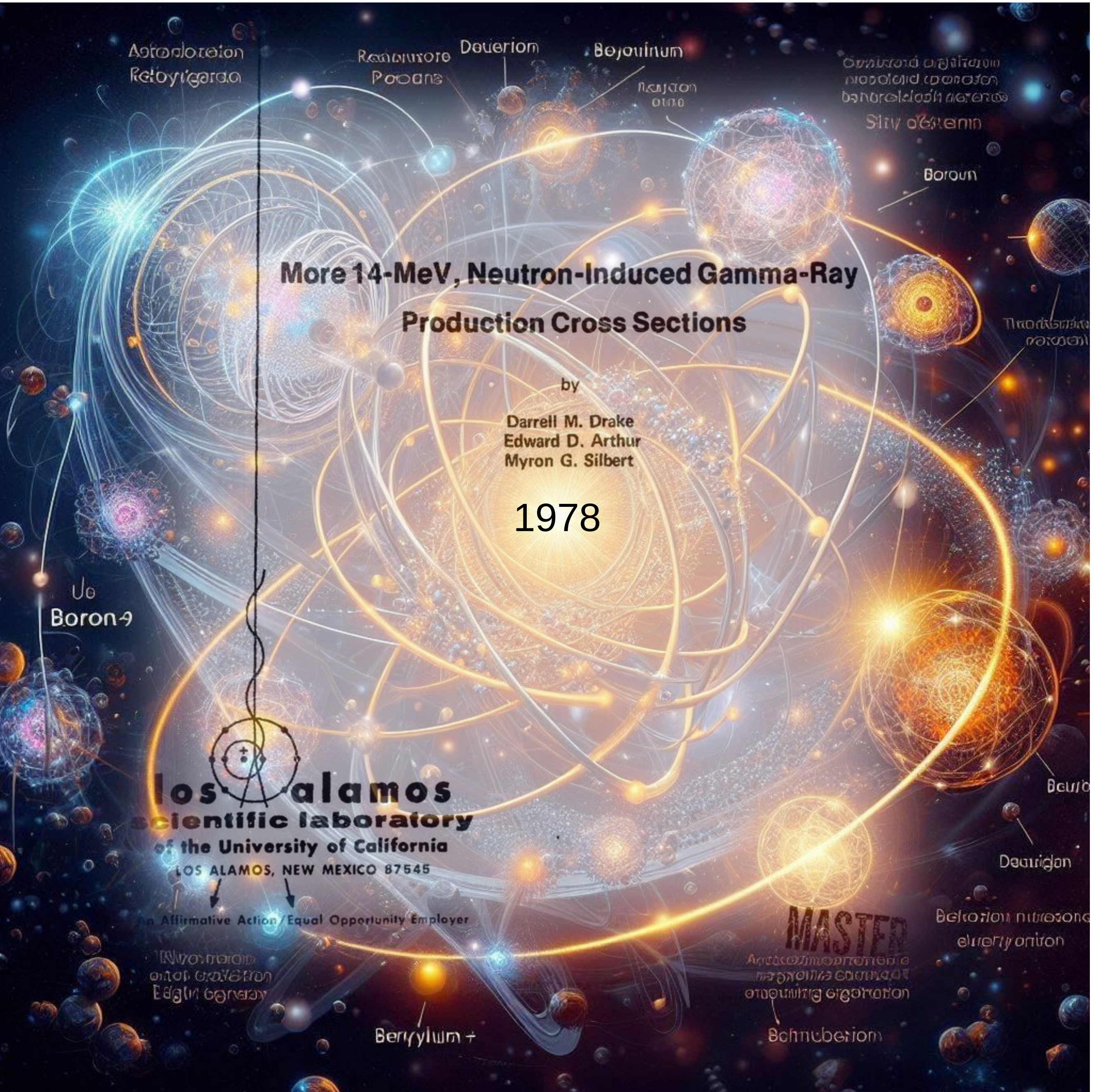
Nuclear Sciences	Natural Sciences	Potential Impact on Human Society
Be-9 is **a stable isotope** with **4p** and **5n**. It plays a crucial role in **neutron moderation** due to its relatively **high neutron scattering cross section.** In nuclear reactors, **Be-9** is used as a **neutron reflector** to enhance neutron flux and improve reactor performance. Its **low thermal neutron capture cross-section** makes it suitable for applications where neutron moderation is essential.	**Be-9** is relevant in cosmogenic studies. It is produced by cosmic ray interactions with nitrogen and oxygen in the Earth's atmosphere. Its presence in meteorites provides insights into the early solar system's nucleosynthesis. Cosmogenic radionuclide (CRN) dating is based on the rate of accumulation of cosmic rays that stimulate the production and decay of radionuclides such as C-14, **Be-10**, Al-26, and Cl-36.	**Be**-alloys have applications in electronics, gyroscopes, springs, electrical contacts, spot-welding electrodes, structural materials for high-speed aircraft, missiles, spacecraft and communication, satellites. semiconductors and X-ray windows. However, beryllium is toxic and poses health risks to humans.







Beryllium and 14-MeV neutrons in Big Bang Nucleosynthesis (BBN)



The BBN theory predicted ^{7}Be destruction via resonance in d + $^{7}Be \rightarrow {}^{9}B$ process.

V. Valkovic, D. Sudac, and J. Obhodas, The role of 14 MeV neutrons in light element nucleosynthesis, ANIMMA 2017 EPJ Web of Conferences 170, 01017 (2018), https://doi.org/10.1051/epjconf/201817001017

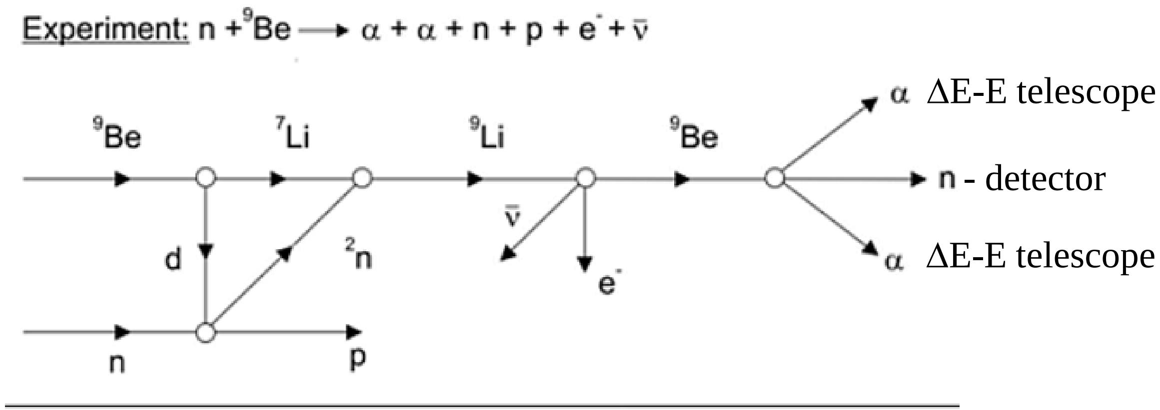


Fig. 4: Incoming neutron interacting with d in ^{9}Be nucleus leading to $^{7}Li + {}^{2}n$ interaction and sequence of decays as indicated.

A pulsed **14.2-MeV** neutron source and **NaI(Tl)** gamma-ray spectrometer were used to measure gamma-ray production cross sections for **beryllium**, carbon, magnesium, aluminum, silicon, **calcium**, titanium, vanadium, chromium, iron, copper, niobium, molybdenum, thorium, and ^{238}U.

No gamma rays were observed from **beryllium-9** except for the **0.48-MeV gamma-ray from $^{9}Be(n, t)^{7}Li^{*}$**, with a cross section of **0.7 ± 0.2 mb/sr**

https://digital.library.unt.edu/ark:/67531/metadc868503/

Which of ^{9}Be, ^{40}Ca, or **^{75}As** would be more suitable for presenting at the ISINN-30, considering its significance in nuclear, natural, life, and environmental sciences, as well as their potential impact on human society?

Nuclear Sciences	Natural Sciences	Potential Impact on Human Society
Arsenic-75 is a radioactive isotope with a half-life of 94.6 days. It is used in tracer studies to investigate chemical reactions, biological processes, and environmental transport. Arsenic-75 emits gamma radiation, making it suitable for radiography and quality control.	Arsenic is a toxic element found in the Earth's crust. Its compounds can contaminate soil and water. It has implications in environmental chemistry, especially in understanding arsenic mobility and remediation.	Arsenic exposure poses serious health risks, including cancer, skin lesions, and cardiovascular diseases. Efforts to mitigate arsenic contamination are critical for public health.

Arsenic was historically used in various products, including pesticides, dyes, and medicines. Forensic historians may analyze historical artifacts or documents to trace the use of arsenic and its impact on human health and criminal activities throughout history.

Arsenic is naturally present at high levels in the groundwater of a number of countries, as Bangladesh, Argentina, Cambodia, Chile, China, India, Mexico, Pakistan, the US and Vietnam.

A patient in Bangladesh with "blackfoot disease," associated with long-term exposure to arsenic.
Seth H. Frisbie

Arsenic compounds are used in LEDs for green and blue light emission, as dopants in semiconductors for devices like transistors, and in thin-film **solar cells** for efficient energy conversion. They're also integral to compound semiconductors for applications in **electronics and optoelectronics**.

https://edition.cnn.com/2024/03/21/climate/arsenic-contaminated-water-bangladesh-climate-intl/index.html

https://www.euronews.com/green/2024/01/18/half-of-bangladeshi-drinking-water-is-polluted-with-arsenic-and-climate-change-is-making-i

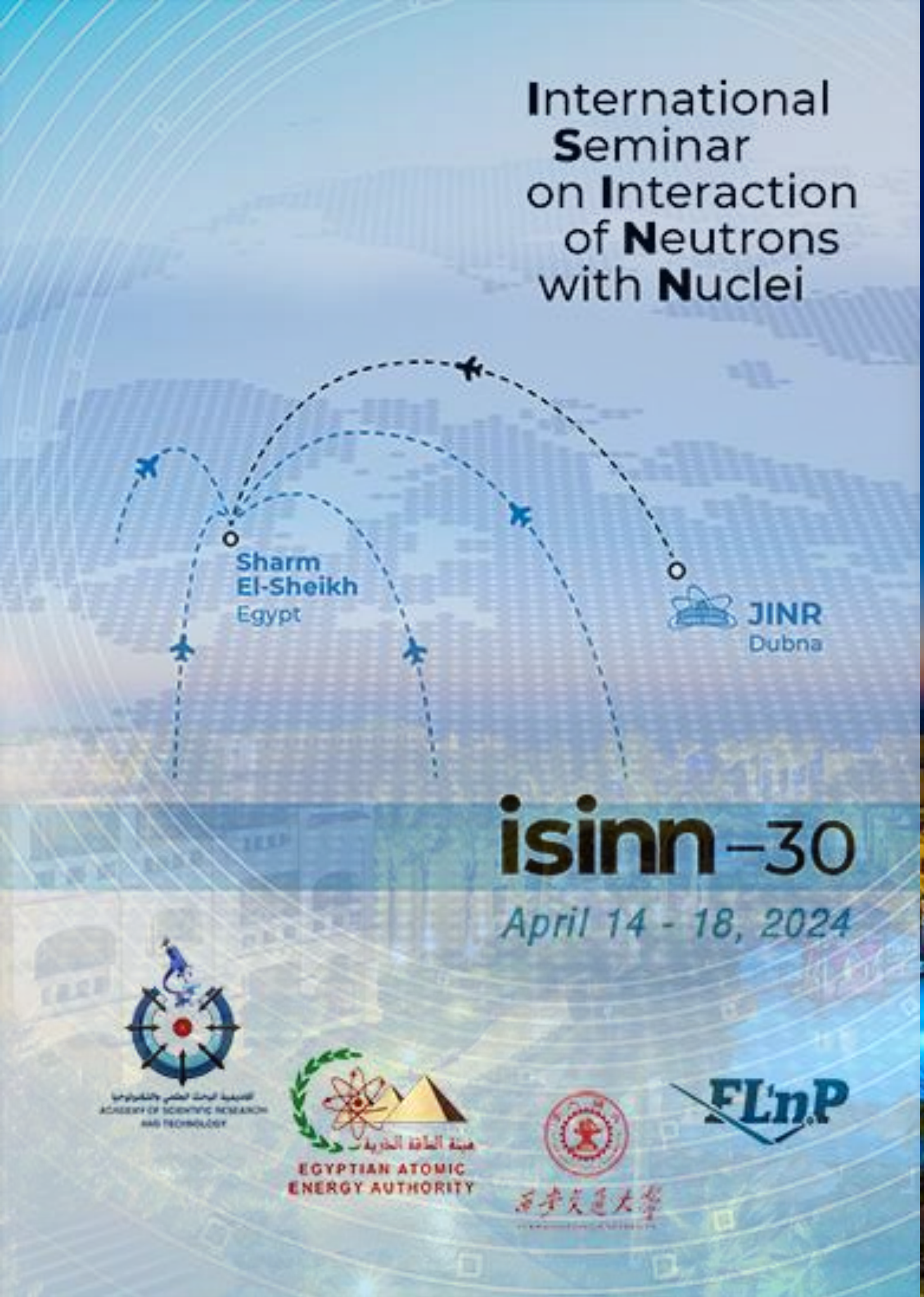
Which of ^{9}Be, **^{40}Ca**, or ^{75}As would be more suitable for presenting at the ISINN-30, considering its significance in nuclear, natural, life, and environmental sciences, as well as their potential impact on human society?

Nuclear Sciences	Natural Sciences	Potential Impact on Human Society
Calcium-40 is a stable isotope abundant in nature. It is relevant in nuclear astrophysics for studying stellar nucleosynthesis. The 40Ca(n,α)37Ar reaction produces radioactive argon-37, which aids in nuclear explosion monitoring. Understanding its thermal neutron cross section is essential for accurate yield predictions.	Calcium is vital for biological processes, including muscle contraction, nerve function, and bone health. It plays a role in geological processes, such as carbonate formation and mineralization.	Calcium supplements are widely used for bone health and preventing osteoporosis. Calcium-based materials find applications in construction, such as cement and concrete.

In summary, each isotope has its unique significance, and the choice for presentation at ISINN-30 would depend on the specific focus of the seminar.

Beryllium-9 and calcium-40 are relevant in nuclear contexts, while arsenic-75 has broader applications in both natural sciences and societal health.

Interaction of 14-MeV neutrons with ^{40}Ca



Ivan Ruskov
for
TANGRA Co

TANGRA Project

Development and application of the tagged neutron method (TNM, API) for elemental analysis and nuclear reaction studies

https://flnp.jinr.int/en-us/main/facilities/tangra-project-en

Figure 1. ING-27 dimensions (mm) and the direction of irradiation of DT-reaction fragments.

The **TANGRA** (**TA**gged **N**eutrons & **G**amma-**RA**ys) are multi-purpose, multifunctional, multi-detector, mobile setups of different geometries, designed for studying the characteristics of the products (characteristic γ-rays and neutrons) in nuclear reactions induced by “tagged” neutrons with energies of 14.1 MeV.

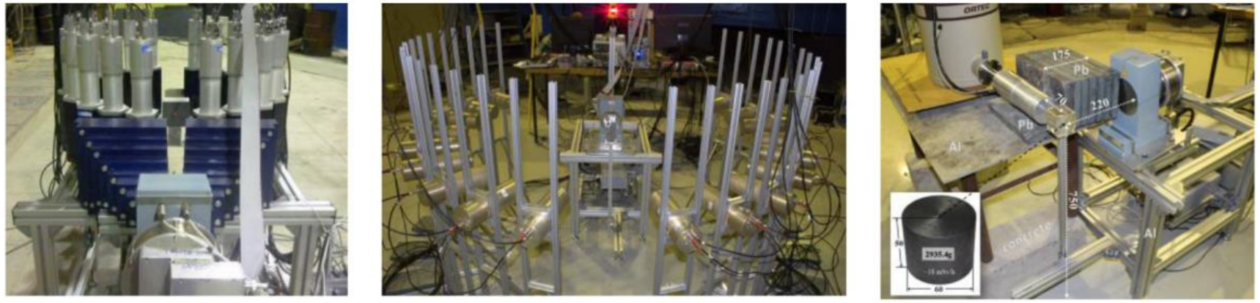
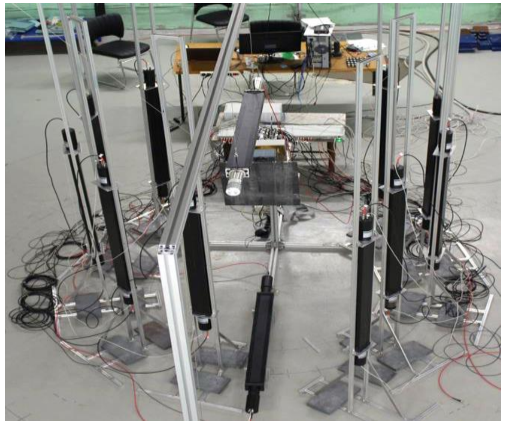
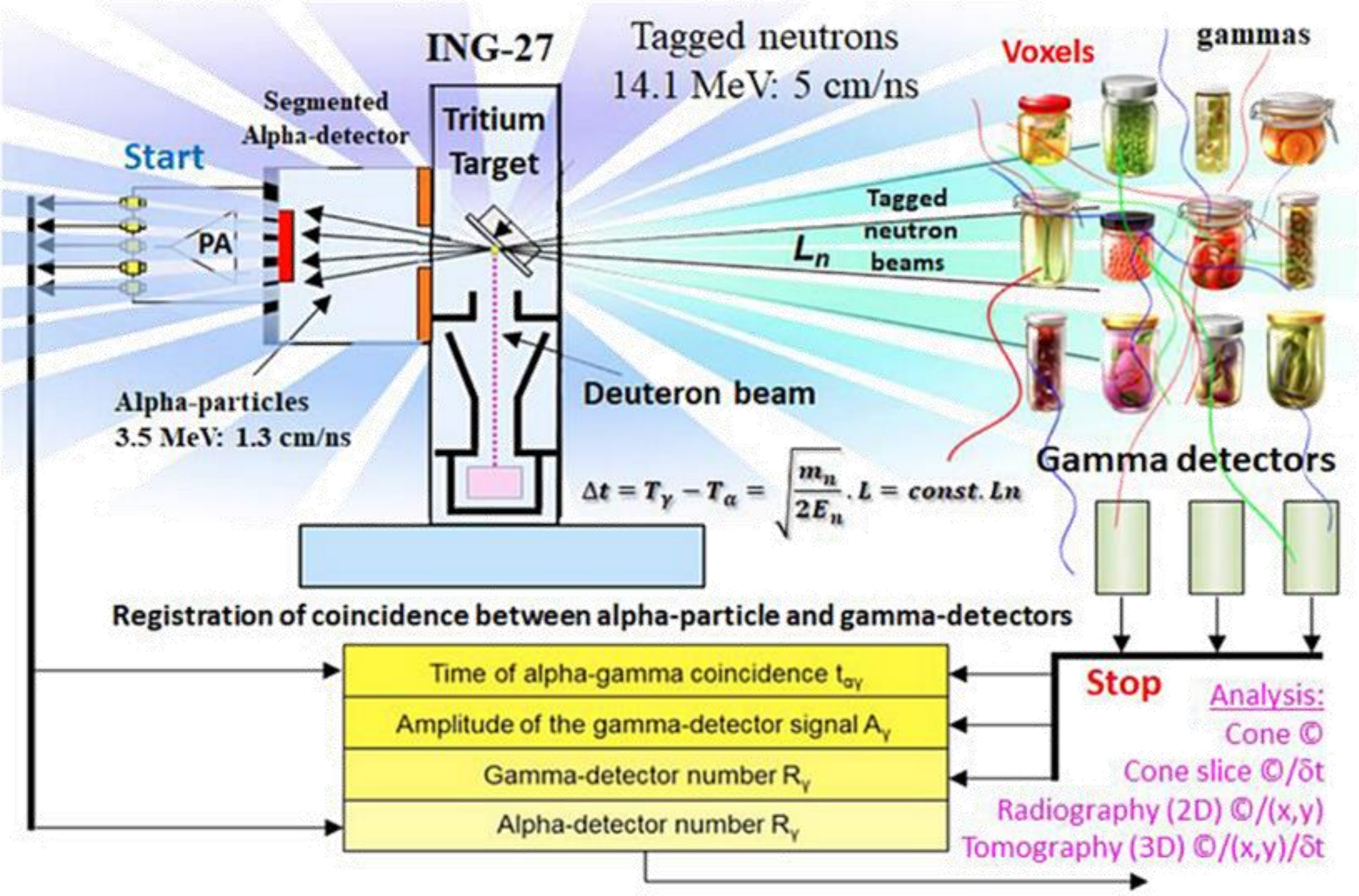
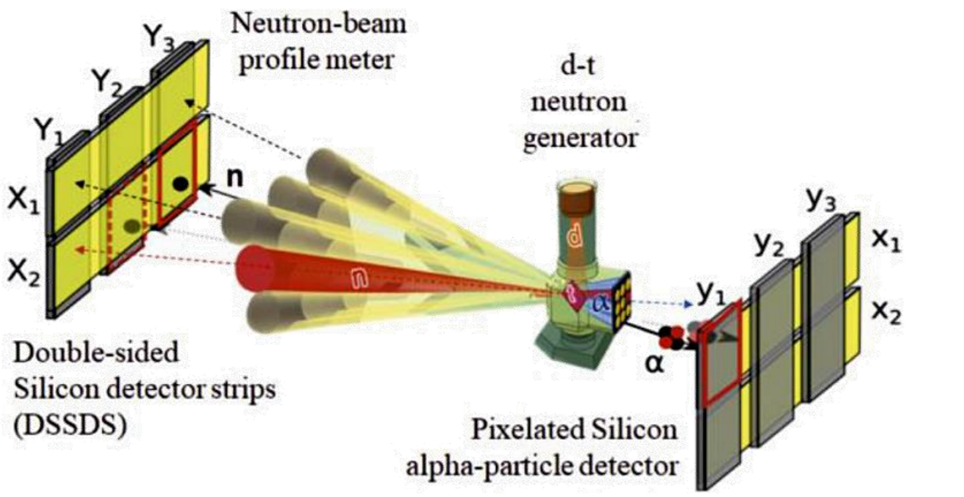


Figure 2. Experimental setups: TANGRA-NaI(Tl) (left), TABGRA-BGO (middle), TANGRA-HPGe (right).

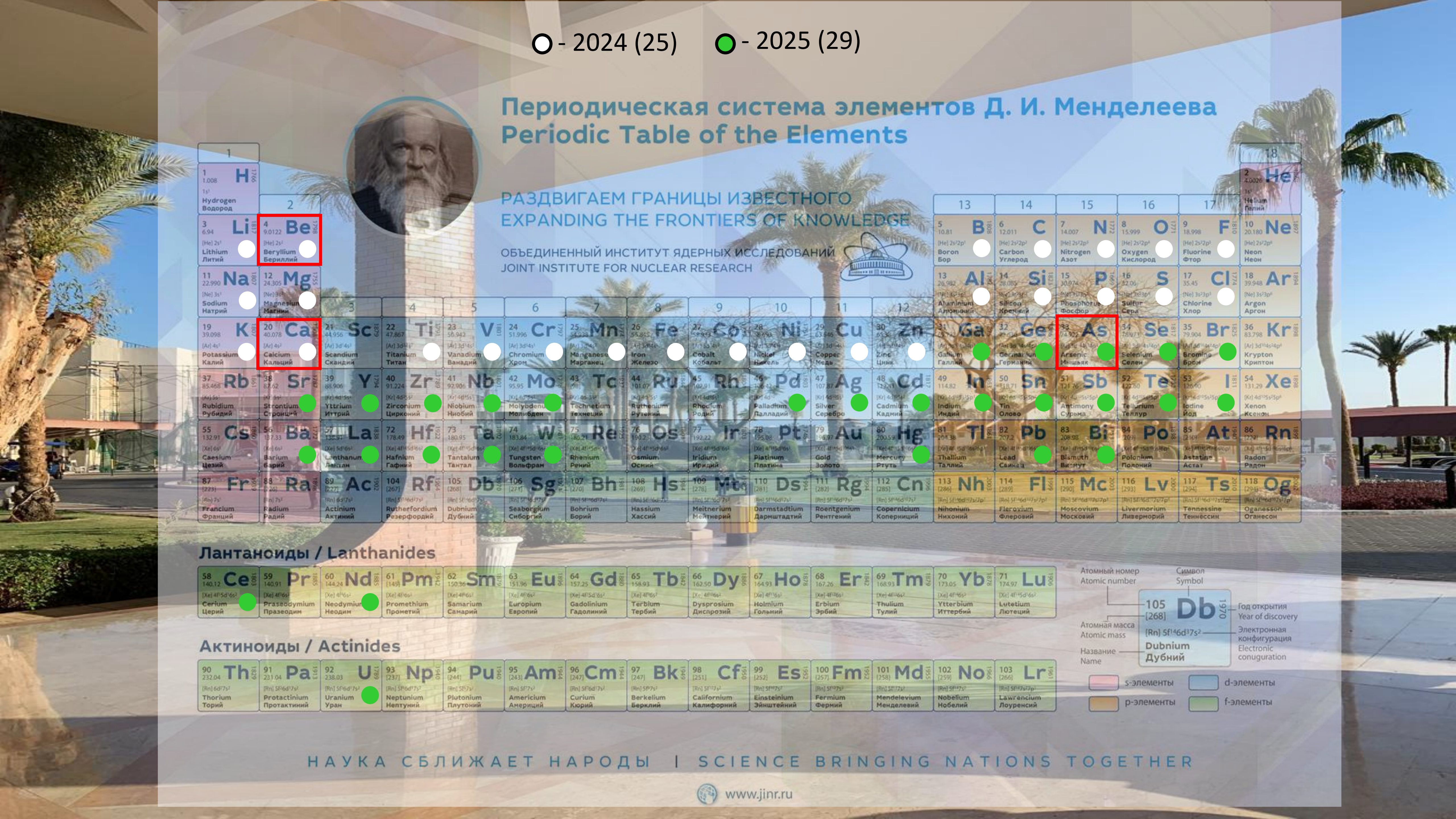


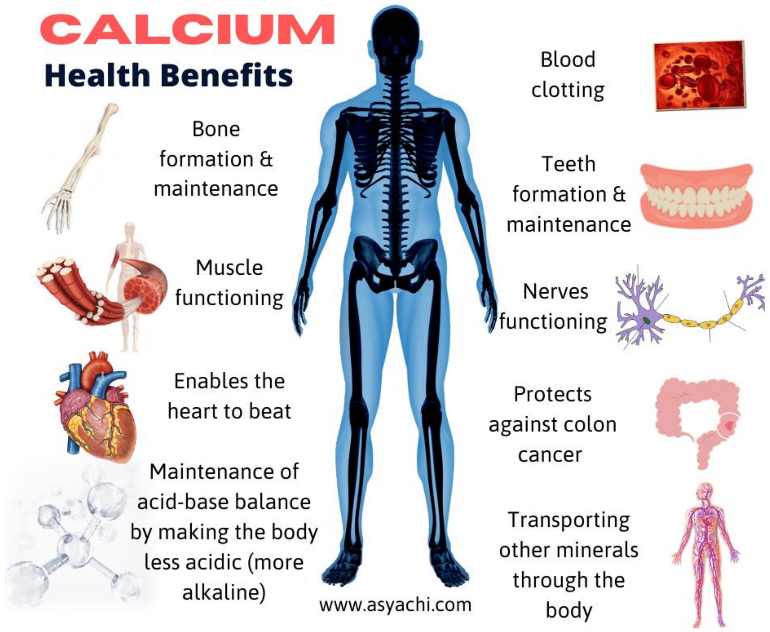
Tagged Neutron Method (TNM). Associated Particle Imaging (API). Time-Correlated Associated Particle Technique (TCAPT).

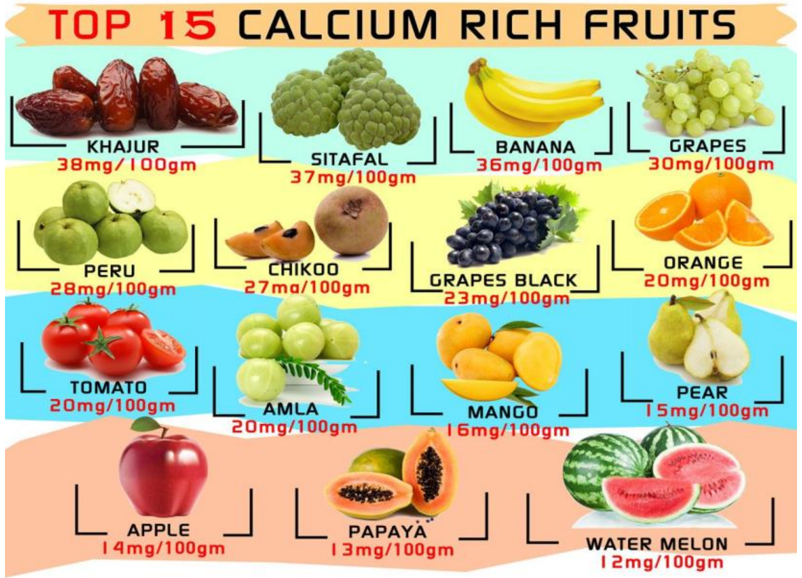




Ivan Ruskov, Yury Kopach, Vyacheslav Bystritsky *et al.*, TANGRA multidetector systems for investigation of neutron-nuclear reactions at the JINR Frank Laboratory of Neutron Physics, EPJ Web of Conferences 256, 00014 (2021). https://doi.org/10.1051/epjconf/202125600014


○ - 2024 (25)
● - 2025 (29)
Периодическая система элементов Д. И. Менделеева
Periodic Table of the Elements
РАЗДВИГАЕМ ГРАНИЦЫ ИЗВЕСТНОГО
EXPANDING THE FRONTIERS OF KNOWLEDGE
ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ
JOINT INSTITUTE FOR NUCLEAR RESEARCH
Лантаноиды / Lanthanides
Актиноиды / Actinides
Атомный номер
Atomic number
Символ
Symbol
Год открытия
Year of discovery
Атомная масса
Atomic mass
Электронная конфигурация
Electronic conguration
Название
Name
s-элементы
d-элементы
p-элементы
f-элементы
НАУКА СБЛИЖАЕТ НАРОДЫ | SCIENCE BRINGING NATIONS TOGETHER
www.jinr.ru


CALCIUM
Health Benefits
Bone formation & maintenance
Muscle functioning
Enables the heart to beat
Maintenance of acid-base balance by making the body less acidic (more alkaline)
www.asyachi.com
Blood clotting
Teeth formation & maintenance
Nerves functioning
Protects against colon cancer
Transporting other minerals through the body


TOP 15 CALCIUM RICH FRUITS
KHAJUR 38mg/100gm
SITAFAL 37mg/100gm
BANANA 36mg/100gm
GRAPES 30mg/100gm
PERU 28mg/100gm
CHIKOO 27mg/100gm
GRAPES BLACK 23mg/100gm
ORANGE 20mg/100gm
TOMATO 20mg/100gm
AMLA 20mg/100gm
MANGO 16mg/100gm
PEAR 15mg/100gm
APPLE 14mg/100gm
PAPAYA 13mg/100gm
WATER MELON 12mg/100gm

Some uses of ^{40}Ca and ^{48}Ca isotopes in nuclear physics

^{40}Ca Isotope:

1. **Doubly Magic Nucleus**: **^{40}Ca** is considered a “doubly magic” nucleus, because it has 20 protons and 20 neutrons, making it very stable[123].

2. **Study of Nuclear Shapes**: The “magic” nature of **^{40}Ca** allows for the coexistence of various shapes of the nucleus that have very similar energies[123].

3. **Potassium Decay/Radiogenic Tracer**: **^{40}Ca** is formed when the radioactive isotope of **potassium-40** decays by **β^-** emission[4] is concentrated in the continental crust and can be used as a tracer for **Ca** fluxes to the ocean[1]

4. **Projectile Fragmentation**: **^{40}Ca** has been used as a primary beam in projectile fragmentation reactions at 140 MeV/nucleon on **^{9}Be** and **^{181}Ta** targets[4].

https://accelconf.web.cern.ch/r08/talks/TUCAU02.pdf

^{48}Ca Isotope:

1. **Doubly Magic Nucleus**: ^{48}Ca is another “doubly magic” nucleus with 20 protons and 28 neutrons[51].

2. **Neutron Distribution**: The neutron distribution of ^{48}Ca has been studied to understand the size of atomic nuclei and the size of neutron stars[5].

3. **Production of New Nuclei**: ^{48}Ca is a valuable starting material for the production of new nuclei in particle accelerators, both by fragmentation and by fusion reactions with other nuclei[6].

4. **Synthesis of Transuranic and Superheavy Elements**: The extreme neutron excess of the ^{48}Ca nucleus enables one to approach the double magic nucleus 298 114 in fusion reactions[7].(JINR U-300 heavy-ion cyclotron)

5. **Double Beta Decay**: ^{48}Ca is the lightest nucleus known to undergo double beta decay and the only one simple enough to be analyzed with the sd nuclear shell model[4].

2024 г. : Results on Gamma-ray production cross section for the interaction of 14-MeV neutrons with:
Li, Be, B, C, N, O, F, Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe , Co, Ni, Cu, Zn.

Neutron Absorption: CaO can absorb neutrons in certain nuclear reactor environments, affecting the neutron flux and potentially serving as a neutron moderator or absorber.

Radiation Shielding: CaO, along with other materials, may be used in the construction of radiation shielding to protect against ionizing radiation emitted from nuclear reactors, radioactive materials, or medical facilities.

Nuclear Waste Immobilization: CaO may be incorporated into materials used for the immobilization and encapsulation of radioactive waste, helping to stabilize and contain hazardous nuclear byproducts.

CaO-based pellets (CPHs) were prepared to capture gaseous **rhenium (Re)** as a surrogate for the **technetium-99 (^{99}Tc)** released from spent nuclear fuels. Re-adsorbed CPH at 900°C (CPR-9) exhibited a high adsorption capacity of 11.47 mol-Re kg−1 and a capture efficiency of > 99%. It was also found to possess excellent thermal stability and mechanical strength, suggesting that CPR-9 is a potential candidate for immobilizing the gaseous ^{99}Tc from spent nuclear fuel.

Seok-Min Hong, Jae-Hwan Yang, Chang Hwa Lee, Ki Rak Lee, Hwan-Seo Park, Development of a CaO-based pellet for capturing gaseous technetium-99 from spent nuclear fuel, Journal of Environmental Chemical Engineering, Volume 10, Issue 6, 2022, 108971, https://doi.org/10.1016/j.jece.2022.108971.

The most commonly used calcium compounds

Calcium Carbonate (**$CaCO_3$**): Used as a filler in ceramics, glass, plastics, and paint.
Calcium Oxide (**CaO**): Also known as quicklime, it's used extensively as a building material and in industrial neutralization reactions.
Calcium Hydroxide (**$Ca(OH)_2$**): Known as slaked lime, it's used in the detection of CO_2.
Calcium Carbide (**CaC_2**): Used in the manufacture of plastics and to make acetylene gas,
Calcium Sulfate (**$CaSO_4$**): Used to make chalk for the blackboard and in its hemihydrate form, is also known as Plaster of Paris, drywall, cement. soil conditioner, firming agent, setting broken bones, moisture indicator, filler in plastics and paints, tofu coagulant, sulfuric acid manufacture.
Calcium Phosphate ($Ca_3(PO_4)_2$): Used in animal feed and fertilizers.
Calcium Stearate: Used in the manufacture of wax crayons, cosmetics, plastics, and paints.
Calcium Chloride (**$CaCl_2$**): It's used as a fertilizer, in wastewater treatment, for dust control, de-icing, and in construction.
Calcium Gluconate (**$C_{12}H_{22}CaO_{14}$**): Used as a food additive.
Calcium Chlorate **($Ca(ClO_3)_2$)** : It's used as an herbicide and in pyrotechnics.

Calcium Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$): More than 99% of **calcium** in the body is in the form of ***calcium hydroxyapatite***, an inorganic matrix of calcium and phosphate that is stored in the bones and teeth.

Calcium Nitrate ($Ca(NO_3)_2$). It is a colorless salt that is highly soluble in water. Used in:
Agriculture: as a fertilizer due to its rich content of readily available nitrate-nitrogen and water-soluble calcium, promoting plant growth and replenishing calcium in the soil.
Waste Water Treatment: as a source of nitrogen to control odor and prevent the formation of hydrogen sulfide.
Construction: It acts as a set accelerator in concrete, reducing the setting time and making the process more efficient.

The transformation by heating **calcium carbonate** **($CaCO_3$)** into **calcium oxide (CaO)** involves a process called **calcination**: **$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$**

TOXIC calcium compounds to be aware of:

Calcium Arsenate (**$Ca(AsO_4)_2$**): Contains arsenic, which is highly toxic. It was used as an ***insecticide*** but is now avoided due to health risks.

Calcium Carbide (**CaC_2**): Used for ***acetylene gas production***, but mishandling can be dangerous.

Calcium Cyanamide (**$CaCN_2$**): Used as a ***fertilizer***, but it releases toxic *hydrogen cyanide gas* upon decomposition.

Quicklime (**CaO**): Highly alkaline and can cause chemical burns. Reacts with water to form calcium hydroxide.

The most commonly used calcium compounds

Calcium-based materials can play important roles in nuclear technology and research in several ways:

Neutron Moderation: Using calcium compounds like **CaO**, **CaF_2** as moderators in nuclear reactors.

Scintillation Detectors: Utilizing **calcium fluoride** (**CaF_2**) as a scintillation material in radiation detectors.

Radiation Shielding: Calcium-containing materials, such as concrete or calcium-based ceramics, can be used as radiation shielding in nuclear facilities. These materials help attenuate radiation and protect workers and the environment from harmful exposure.

Target Materials: Calcium targets may be used in research reactors or particle accelerators for producing medical isotopes or conducting nuclear physics experiments. **Calcium-48**, for example, is used as a target material for producing positron emitters like fluorine-18, which is widely used in positron emission tomography (PET) imaging.

Neutron Activation Analysis: Utilizing **calcium-48** (**^{48}Ca**) as a neutron activation target in analytical techniques.

Nuclear Waste Management: Calcium-based materials may be incorporated into waste forms for immobilizing radioactive waste. Calcium silicate glasses or ceramics are potential candidates for encapsulating radioactive elements, providing long-term stability and containment.

Nuclear Medicine: While not directly related to nuclear reactors, calcium-based compounds have applications in nuclear medicine. Calcium tracers labeled with radioisotopes are used in diagnostic imaging techniques like bone scans to visualize bone structure and detect abnormalities. Using **calcium-41** (**^{41}Ca**) as a tracer for studying calcium metabolism in biological tissues.

Radiometric Dating: Employing **calcium-40** (**^{40}Ca**) decay in potassium-argon dating for determining rock ages.

JRC GEEL

Neutron inelastic cross-sections on ^{40}Ca

IFIN-HH

Marian Boromiza[1], Catalin Borcea[1], Philippe Dessagne[2], Greg Henning[2], Maëlle Kerveno[2], Alexandru Negret[1], Markus Nyman[3], Adina Olacel[1], Andreea Oprea[3], Carlos Paradela[3], Arjan Plompen[3]

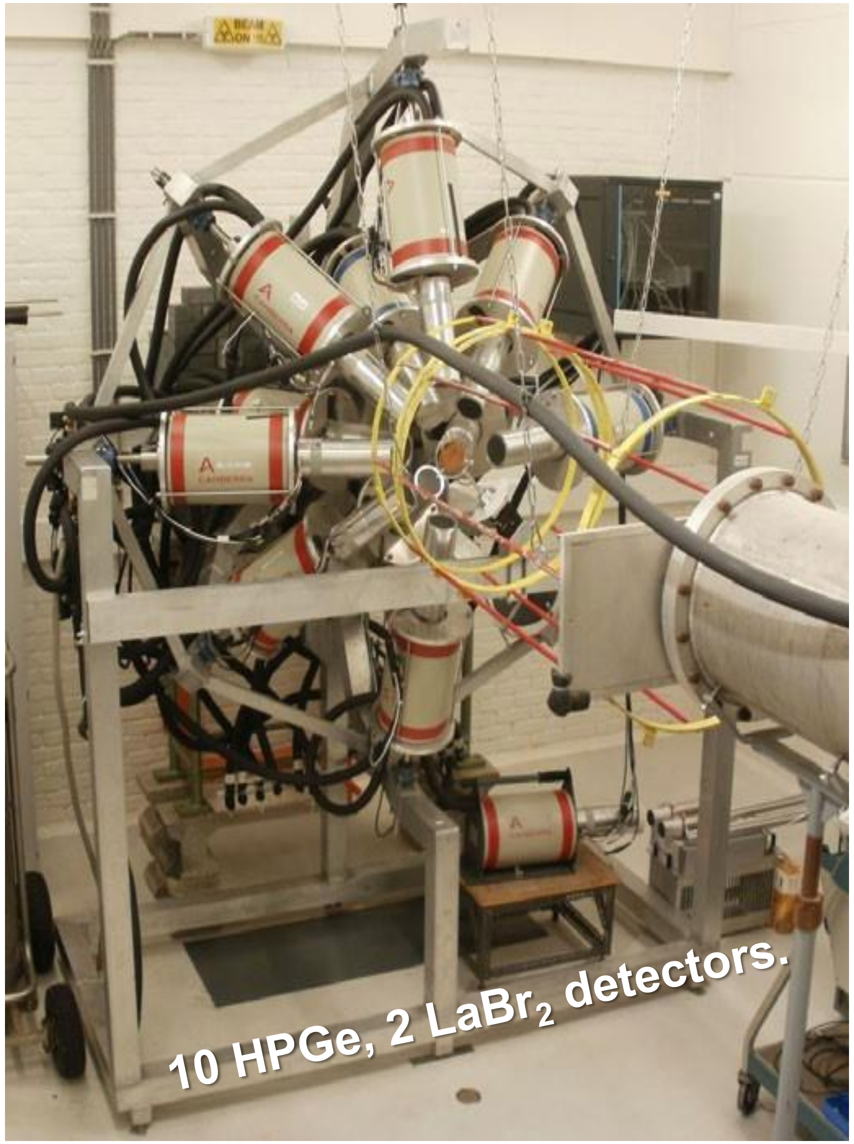
[1]Horia Hulubei National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania
[2]Université de Strasbourg, CNRS, IPHC Strasbourg, France
[3]European Commission, Joint Research Center, Geel, Belgium

GAINS: Gamma Array for Inelastic Neutron Scattering

^{40}Ca is crucial for Molten Salt Reactors (MSRs), but experimental data on its inelastic cross sections are sparse. Detailed handling of CN spin-parity population differences is essential for both capture and inelastic channels. Experiments were conducted at GELINA with the GAINS spectrometer. Gamma spectroscopy, coupled with neutron time-of- flight, determined inelastic neutron cross sections. Preliminary results indicate significant disparities between collected data and evaluations, with minimal statistics leading to a reported 10% uncertainty. Multiple scattering corrections are required for further refinement.

MONNET

GELINA



https://indico.cern.ch/event/1201892/attachments/2574446/4753928/WINS_2023_Meeting_Minutes.pdf

*WORK SUPPORTED BY ROMANIAN FUNDING AGENCIES THROUGH RESEARCH GRANT PN-III-P1-1.1-PD-2021-0207

WINS 2023

Oct 10 – 12, 2023
Rensselaer Polytechnic Institute
US/Eastern timezone

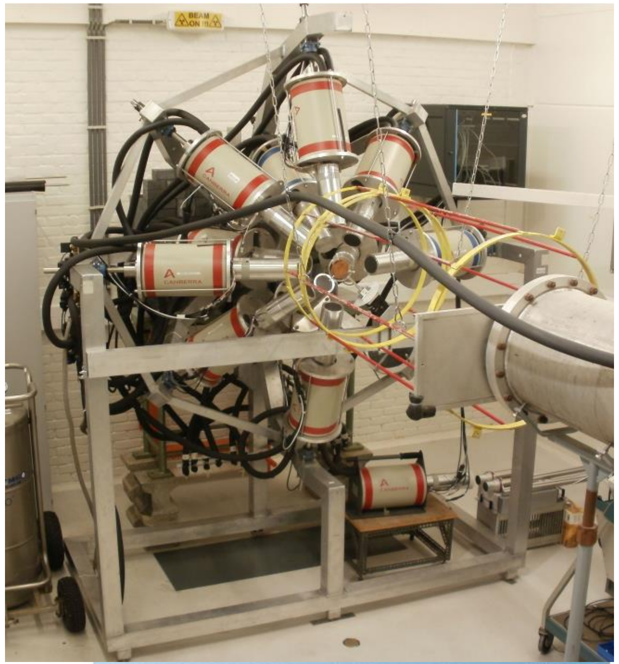
Workshop on Elastic and Inelastic Neutron Scattering

10-12 Oct. 2023, Troy, USA

https://indico.cern.ch/event/1201892/contributions/5529656/

Neutron inelastic cross-sections on ^{40}Ca

Marian Boromiza[1], Catalin Borcea[1], Philippe Dessagne[2], Greg Henning[2], Maëlle Kerveno[2], Alexandru Negret[1], Markus Nyman[3], Adina Olacel[1], Andreea Oprea[3], Carlos Paradela[3], Arjan Plompen[3]



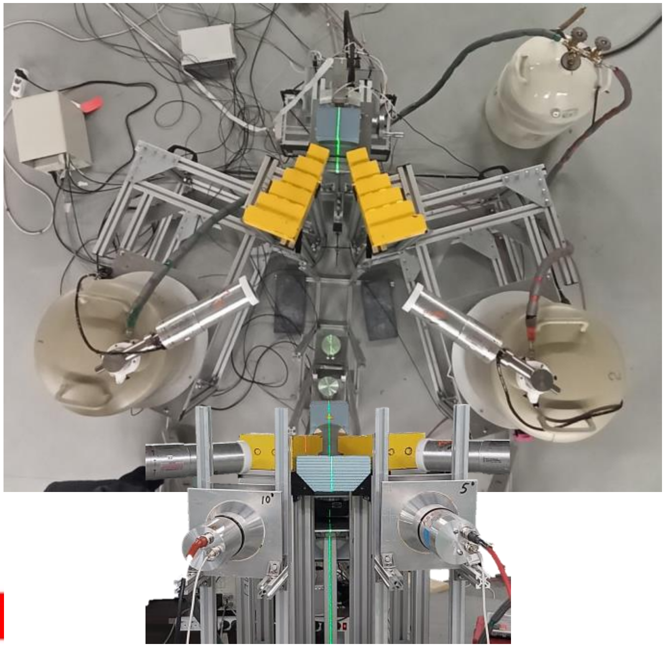
- Flight path 3 @ 100 m
  - good neutron energy resolution
  - **@ 100 m**: 3 keV at 1 MeV, 80 keV at 10 MeV
- 12 HPGe detectors @ 110°, 150° and 125°, d=17 cm
- Large volume: relative efficiency 100%
- FWHM typically ≈ 3 keV @ 1332 keV (^{60}Co)
- Digital acquisition (ACQIRIS digitizers)
  - 12 bit amplitude resolution (4096 channels)
  - 420 MS/s (2.38 ns sampling period)
- **Target**: calcium fluoride compound (CaF_2)
- **Fission chamber (with ^{235}U deposits) to monitor the neutron flux - ^{235}U(n,f) normalization**
- **Time of Flight (ToF) & γ-spectroscopy techniques:**
  - n time of flight → E_n

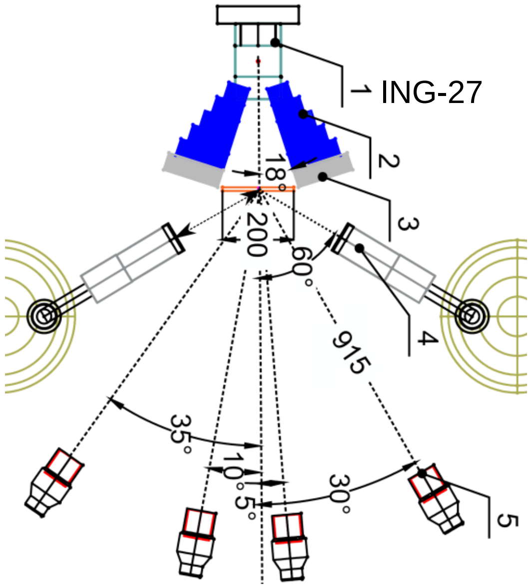
73-rd International conference on nuclear physics "Nucleus-2023: Fundamental problems and applications", 9-13 Oct. 2023, Sarov, Russia

FLNP

Yields of γ-quanta emitted by calcium during 14.1 MeV neutrons irradiation

Fedorov N.A. *, Grozdanov D.N., Kopatch Yu.N., Skoy V.R., Tretyakova T.Yu., Hramco K., Ruskov I.N., Akhmedov G., Berikov D., Andreev A.V., Filonchik P.G. and "TANGRA" collaboration
nfedorov@jinr.ru





WINS 2023

Oct 10 – 12, 2023
Rensselaer Polytechnic Institute
US/Eastern timezone

Workshop on Elastic and Inelastic Neutron Scattering

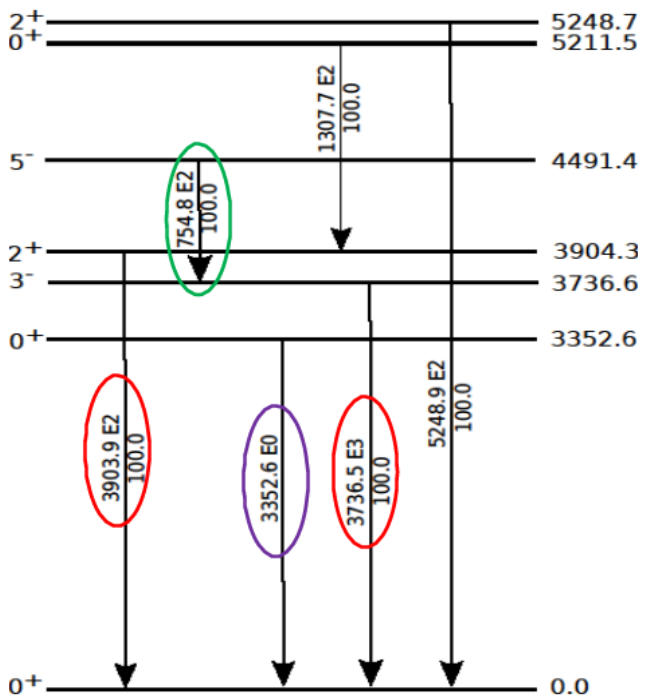
10-12 Oct. 2023, Troy, USA

Neutron inelastic cross-sections on ^{40}Ca

Marian Boromiza[1], Catalin Borcea[1], Philippe Dessagne[2], Greg Henning[2], Maëlle Kerveno[2], Alexandru Negret[1], Markus Nyman[3], Adina Olacel[1], Andreea Oprea[3], Carlos Paradela[3], Arjan Plompen[3]

IFIN-HH

Preparing the experiment: main difficulties



- Target preparation: compound CaF_2 (as ^{40}Ca has a 96.9 % natural abundance):
  - Weak transitions: thick target
  - Keep the ψ self-attenuation + MSC to reasonable values:
  - 2 mm thickness and 76 mm diameter (beam: 61 mm)
- Very high energy ψ rays: 3736 keV (3^-), 3903 keV (2^+) and 5248 keV (2^+):
  - large volume HPGe
  - tricky efficiency extrapolation up to 4 or even 5 MeV
- 3352 keV E0-totally converted☹
- Additional transitions? Maybe 754 keV…
- We expected **Doppler broadenings** of the peaks of interest: $T_{1/2}$ of 41 ps (3736 keV) and 35 fs (3903 keV)

73-rd Int. conf. on nuc. physics "Nucleus-2023: Fundamental problems and applications", 9-13 Oct. 2023, Sarov, Russia

2023 ЯДРО

Yields of γ-quanta emitted by calcium during 14.1 MeV neutrons irradiation

Fedorov N.A. *, Grozdanov D.N., Kopatch Yu.N., Skoy V.R., Tretyakova T.Yu., Hramco K., Ruskov I.N., Akhmedov G., Berikov D., Andreev A.V., Filonchik P.G. and "TANGRA" collaboration
nfedorov@jinr.ru

E, keV	Y	Talys	Simakov	E_i keV, J^P_i	E_f keV, J^P_f	Reaction
754,7397	56±3	30,1	63±3	4491,4 (5^-)	3736,7 (3^-)	$^{40}Ca(n,n')^{40}Ca$
770,313	107±4	44,2		800,1 (2^-)	29,8 (3^-)	$^{40}Ca(n,p)^{40}K$
891,398	88±6	32,8	46±3	891,4 (5^-)	0 (4^-)	$^{40}Ca(n,p)^{40}K$
1157,019		11,3	25±3	1157 (2^+)	0 (0^+)	$^{44}Ca(n,n')^{44}Ca$
1158,925	38±6	8,4		1959,1 (2^+)	800,1 (2^-)	$^{40}Ca(n,p)^{40}K$
1374,42	10±2	9,6		5278,8 (4^+)	3904,4 (2^+)	$^{40}Ca(n,n')^{40}Ca$
1409,84	16±2	14,7		1409,8 ($1/2^+$)	0 ($3/2^+$)	$^{40}Ca(n,\alpha)^{37}Ar$
1611,28		48,2	57±2	1611,3 ($7/2^-$)	0 ($3/2^+$)	$^{40}Ca(n,\alpha)^{37}Ar$
1613,809	20±4	7,5		1643,6 (0^+)	29,8 (3^-)	$^{40}Ca(n,p)^{40}K$
2217	34±8	19,8		2217 ($7/2^+$)	0 ($3/2^+$)	$^{40}Ca(n,\alpha)^{37}Ar$
2230,57	8±3	5,6		2260,4 (3^+)	29,8 (3^-)	$^{40}Ca(n,p)^{40}K$
2796,15	19±10	12,5	30±1	2796,1 ($5/2^+$)	0 ($3/2^+$)	$^{40}Ca(n,\alpha)^{37}Ar$
2814,3	14±7	37,6		2814,3 ($7/2^-$)	0 ($3/2^+$)	$^{40}Ca(n,d)^{39}K$
3736,69	100,0	100,0	100,0	3736,7 (3^-)	0 (0^+)	$^{40}Ca(n,n')^{40}Ca$
3904,38	31±7	34,9	41±2	3904,4 (2^+)	0 (0^+)	$^{40}Ca(n,n')^{40}Ca$
5629,41	15±5	3,3		5629,4 (2^+)	0 (0^+)	$^{40}Ca(n,n')^{40}Ca$

International Atomic Energy Agency

INDC(CCP)-413
Distr. G+RP

September 1998

INDC

INTERNATIONAL NUCLEAR DATA COMMITTEE

S. P. Simakov[1], A. Pavlik[2], H. Vonach[2], S. Hlaváč[3]

STATUS OF EXPERIMENTAL AND EVALUATED DISCRETE γ-RAY PRODUCTION AT E_n=14.5 MeV

Final Report of Research Contract 7809/RB, performed under the CRP on Measurement, Calculation and Evaluation of Photon Production Data

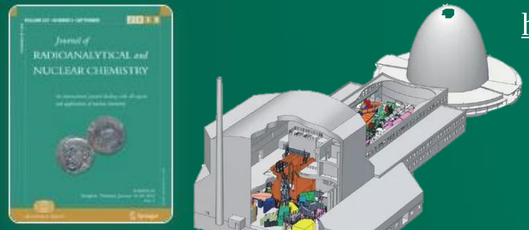
20-Calcium (40 - 96.9, 42 - 0.7%, 43 - 0.1%, 44 - 2.1%, 48 - 0.2%)													
770	^{40}Ca(n,p)^{40}K	$800(2^-)\rightarrow30(3^-)$, p	14.7	90	Ca:∅38.1×76.2, +/+	NaI(Tl)	70±15	Engesser	1967	1.0	?		70±15
892	^{40}Ca(n,p)^{40}K	$892(5^-)\rightarrow0(4^-)$, p	14.1	90	Ca:∅??×20, +/+	Ge(Li)	31±10	Grenier	1974	1.0	?		31±10
			14.7	90	Ca:∅38.1×76.2, +/+	NaI(Tl)	60±13	Engesser	1967	1.0	?		60±13
1157	^{44}Ca(n,n')^{44}Ca	$1157(2^+)\rightarrow0(0^+)$ p	14.1	90	Ca:∅??×20, +/+	Ge(Li)	30±10	Grenier	1974	1.0	?		30±10
			14.7	90	Ca:∅38.1×76.2, +/+	NaI(Tl)	28±4	Engesser	1967	1.0	?		28±4
1611	^{40}Ca(n,α)^{17}Ar	$1611(7/2^-)\rightarrow30(3/2^+)$, p	14.1	90	Ca:∅??×20, +/+	Ge(Li)	29±10	Grenier	1974	1.0	?		29±10
			14.7	90	Ca:∅38.1×76.2, +/+	NaI(Tl)	68±8	Engesser	1967	1.0	?		68±8
2796	^{40}Ca(n,α)^{17}Ar	$2796(5/2^+)\rightarrow0(3/2^+)$, p	14.7	90	Ca:∅38.1×76.2, +/+	NaI(Tl)	34±8	Engesser	1967	1.0	?		34±8
3736	^{40}Ca(n,n')^{40}Ca	$3736(3^-)\rightarrow0(0^+)$, p	14.1	90	Ca:∅??×20, +/+	Ge(Li)	109±28	Grenier	1974	1.0	?		109±28
			14.7	90	Ca:∅38.1×76.2, +/+	NaI(Tl)	113±23	Engesser	1967	1.0	?		113±23
3904	^{40}Ca(n,n')^{40}Ca	$3904(2^+)\rightarrow0(0^+)$, p	14.7	90	Ca:∅38.1×76.2, +/+	NaI(Tl)	48±16	Engesser	1967	1.0	?		48±16
			14.1		Ca:∅30×50, 20.4g, +/+	NaI(Tl)	43±15	Roturier	1966	1.0	?		43±15

https://www-nds.iaea.org/publications/indc/indc-ccp-0413.pdf

Home > Journal of Radioanalytical and Nuclear Chemistry > Article

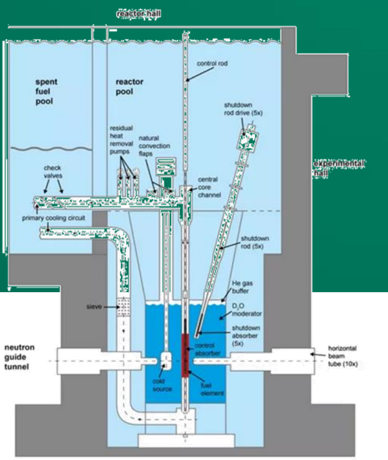
Fast neutron induced gamma rays from (n,n'), (n,p) and (n,α) reactions on $CaCO_3$

Open access | Published: 02 November 2022
Volume 331, pages 5729–5740, (2022) Cite this article
https://doi.org/10.1007/s10967-022-08594-6



Journal of Radioanalytical and Nuclear Chemistry

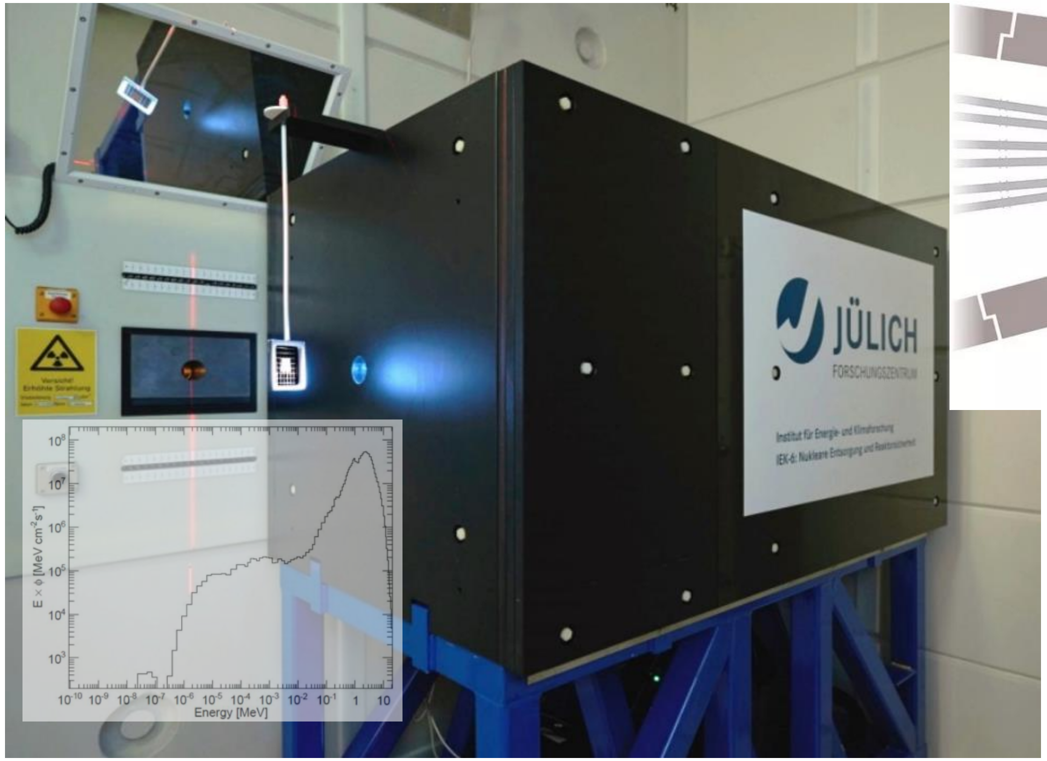
https://doi.org/10.17815/jlsrf-1-54

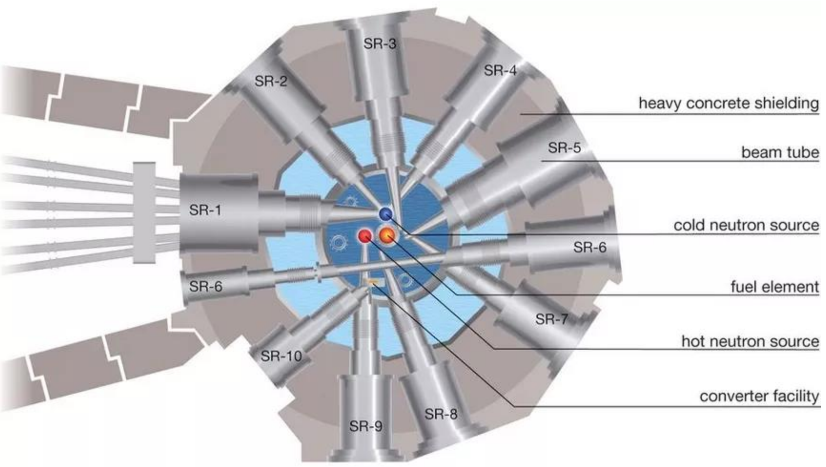


Emission of prompt gamma rays following (n, n'), (n, p) and (n, α) reactions induced by irradiation of a calcium carbonate (**$CaCO_3$**) sample with a beam of fission neutrons was investigated with a modified version of the FaNGaS (Fast Neutron induced Gamma-ray Spectrometry) instrument operated at the Heinz Maier-Leibnitz Zentrum (MLZ) in Garching.

Detector system

- **GMX50-83 n-type HPGe** detector, electrically cooled, 50% relative efficiency, $\Delta E_\gamma \cong 2.1$ keV @1332 keV
- Detector shielding: **PE** (30cm) **B_4C** (1cm) and **Pb** (15cm) mounted on a steel table with wheels to make the system movable.
- DSPEC-50 spectrum acquisition, MAESTRO and GAMMA-Vision evaluation software (ORTEC) and HYPERMET-PC





Neutron source

- Converter facility at FRM II consisting of 2 plates of 93 % enriched U-235
- Two collimators of stacked PE, B_4C and Pb with total length of 101 cm in the beam line restrict the fast beam to 5 cm diameter.
- $\langle E_n \rangle = 2.12 \pm 0.08$ MeV
- $\Phi = (1.01 \pm 0.042) \times 10^8\ cm^{-2}s^{-1}$

Ahmed, M., & Demidov, M. (1978). Atlas of Gamma-Ray Spectra from the Inelastic Scattering of Reactor Neutrons. Moscow: Atomizdat.

https://www.frm2.tum.de/en/frm2/the-neutron-source/reactor/guiding-the-beams/

A digitized version of the database is available at nucleardata.berkeley.edu/atlas

NAVAL NUCLEAR LABORATORY

The Atlas of Gamma-ray Spectra from the Inelastic Scattering of Reactor Fast Neutrons

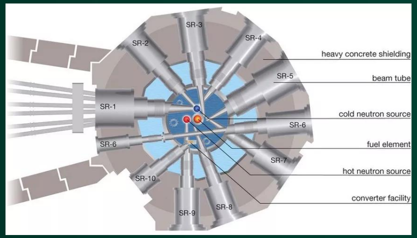
Amanda Lewis[1], Lee Bernstein[2,3], Aaron Hurst[3]

The Naval Nuclear Laboratory is operated for the U.S. Department of Energy by Fluor Marine Propulsion, LLC, a wholly owned subsidiary of Fluor Corporation.

[1] Naval Nuclear Laboratory
[2] Lawrence Berkeley National Laboratory
[3] University of California, Berkeley

https://conferences.lbl.gov/event/504/contributions/4101/attachments/3094/1691/ALewis_WANDA2021.pdf

Home > Journal of Radioanalytical and Nuclear Chemistry > Article

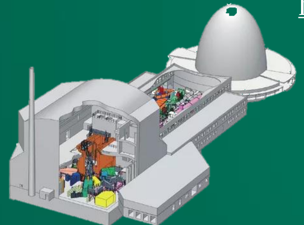


Fast neutron induced gamma rays from (n,n'), (n,p) and (n,α) reactions on $CaCO_3$

Open access | Published: 02 November 2022

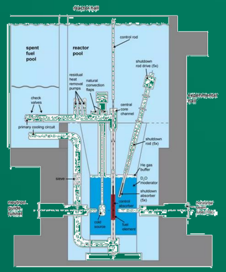
Volume 331, pages 5729–5740, (2022) Cite this article

Ahmed, M., & Demidov, M. (1978). Atlas of Gamma-Ray Spectra from the Inelastic Scattering of Reactor Neutrons. Moscow: Atomizdat.



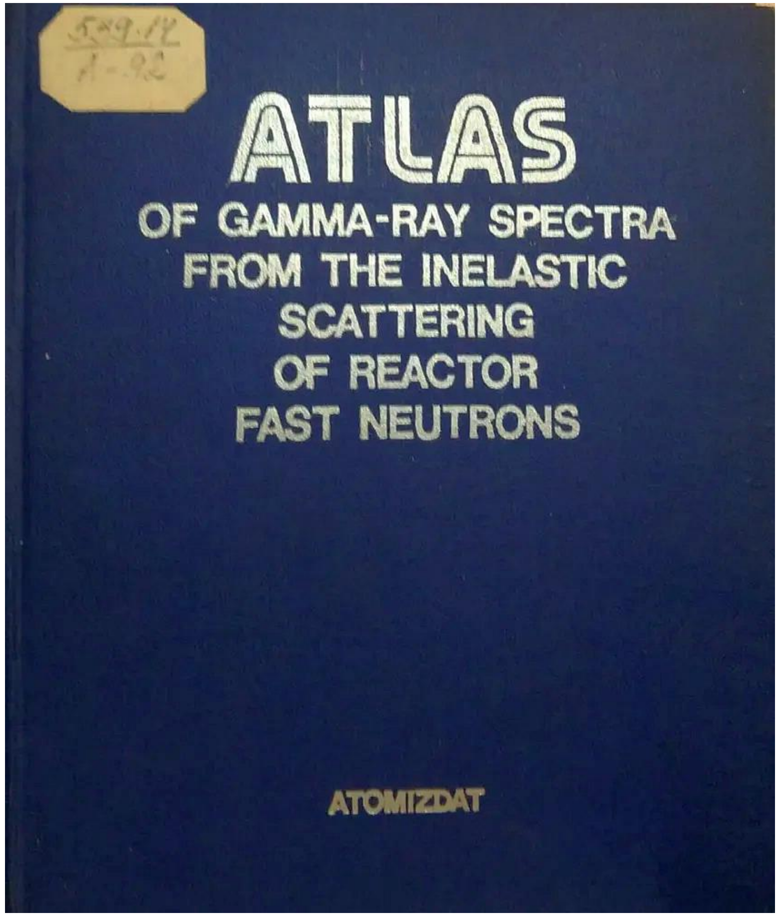
Journal of Radioanalytical and Nuclear Chemistry

https://doi.org/10.17815/jlsrf-1-54



Atlas of Gamma-Ray Spectra from the Inelastic Scattering of Reactor Fast Neutrons

https://www-nds.iaea.org/exfor//servlet/X4sX4arc?op=ge&entry=31816&reqx=7448



The aim is to develop a modern comprehensive catalogue on (n, n'γ)-reactions by verifying and extending the only available database in this field:

the “Atlas of Gamma-rays from the Inelastic Scattering of Reactor Fast Neutrons” published in 1978 by Demidov et al. [1].

From this Atlas a relational database of inelastic neutron scattering (n, n'γ) data has been recently developed [2]

[1] Demidov A, Govor L, Cherepantsev M, Ahmed S, Al-Najiar M, Al-Amili N, Al-Assafi N, Rammo N (1978) Atlas of gamma-ray spectra from the inelastic scattering of reactor fast neutrons. Atomizdat, Moscow

[2] Hurst AM, Bernstein LA, Kawano T, Lewis AM, Song K (2021) The Baghdad Atlas: a relational database of inelastic neutron-scattering (n, n',γ) data. Nucl. Instrum. Meth. A 995:165095

The "Baghdad Atlas" [1] is a large compilation of identified gamma-ray intensities from a fast reactor spectrum

- The neutron source was the Al-Tuwaitha research facility outside of Baghdad in the 1970s
  - A low-energy filter was used to simulate a fast reactor spectrum
- All intensities were measured in reference to the 847 keV gamma ray in ^{56}Fe
- A single Ge(Li) detector at 90° measured the gamma rays from 105 targets
- Uncertainties
  - Flux — No model of the reactor, so this is determined by fitting
  - Statistics
  - Detector efficiency
  - Non-linearity in energy
  - Gamma-ray self-absorption

  (Statistics, Detector efficiency, Non-linearity in energy, Gamma-ray self-absorption) — Provided by the experimentalists (at 2-sigma)
  - Sample — Given with the normalization to ^{56}Fe

$_{26}$**Fe**

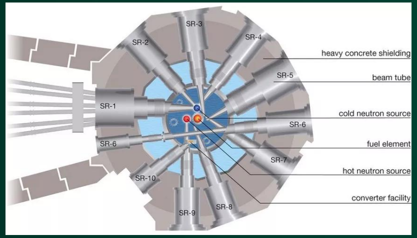
E_γ	I_γ	^AZ	E_i
1165.9 (6)	0.08 (3)		
1173.? (8)	0.25 (10)		[illegible]6
1175.0 (8)	0.15 (10)		[illegible]4
[illegible]	[illegible]		
1238.3 (2)	10.5 (5)	^{58}Fe	2085.1
[illegible]	[illegible]	^{56}Fe	4395.4
1298.9 (4)	0.12 (4)		
1303.2 (3)	0.64 (10)	[illegible]	[illegible]
1334.6 (4)	0.18 (3)		
[illegible]	[illegible]		
1386.6 (10)	0.06 (3)		
[illegible]	[illegible]	^{55}Fe	1408.2
1434.2 (10)	0.05 (2)		

3% uncertainty (1238.3 (2), 10.5 (5))

25% uncertainty (1386.6 (10), 0.06 (3))

[1] A. M. Demidov, et. al., Atlas of Gamma-ray Spectra from the Inelastic Scattering of Reactor Fast Neutrons, Moscow, Atomizdat (1978)

NAVAL NUCLEAR LABORATORY

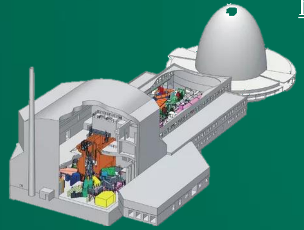


Fast neutron induced gamma rays from (n,n'), (n,p) and (n,α) reactions on $CaCO_3$

Open access | Published: 02 November 2022

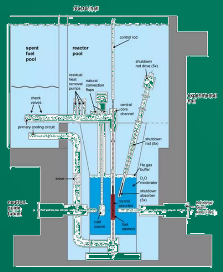
Volume 331, pages 5729–5740, (2022) Cite this article

Ahmed, M., & Demidov, M. (1978). Atlas of Gamma-Ray Spectra from the Inelastic Scattering of Reactor Neutrons. Moscow: Atomizdat.



Journal of Radioanalytical and Nuclear Chemistry

https://doi.org/10.17815/jlsrf-1-54



Atlas of Gamma-Ray Spectra from the Inelastic Scattering of Reactor Fast Neutrons

https://www-nds.iaea.org/exfor//servlet/X4sX4arc?op=ge&entry=31816&reqx=7448

The HPNSRL Website and the Baghdad Atlas

CRP: Nuclear Data Portal Web Tools

https://www-nds.iaea.org/index-meeting-crp/WebToolsCM/docs/Hurst_IAEA_2018.pdf

Aaron M. Hurst

amhurst@berkeley.edu

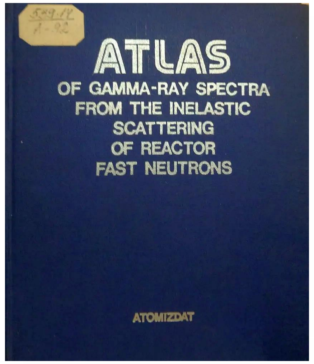
Department of Nuclear Engineering
University of California, Berkeley

July 30 – August 1, 2018

NSSC 8
NUCLEAR SCIENCE and SECURITY CONSORTIUM

THE UNIVERSITY OF CALIFORNIA BERKELEY 1868 LET THERE BE LIGHT

"The Baghdad Atlas": Fast neutron γ-ray data from (n, n')



- Compilation of energy-integrated inelastic neutron-scattering $(n, n'\gamma)$ data disseminated in book format
- ~ 7000 γ rays (E_γ and BR) from 105 samples: 76 natural and 29 isotopically-enriched targets
- Set of consistent measurements performed under identical conditions
- DAQ using Ge(Li) detector on fast neutron beam line at the IRT-5000 Reactor: Al-Tuwaitha Research Facility, Baghdad, Iraq

Thanks to Andrej Trkov (IAEA) for rescuing the book!

“The Baghdad Atlas”: The IRT-5000 Reactor Fast neutron γ-ray data from (n, n')

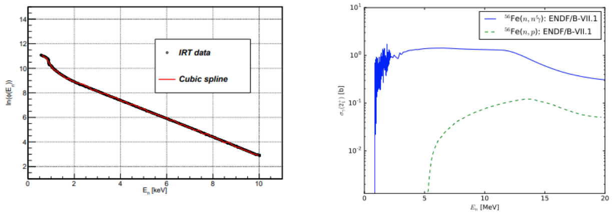
https://www-nds.iaea.org/index-meeting-crp/WebToolsCM/docs/Hurst_IAEA_2018.pdf

Inelastic $(n, n'\gamma)$ reactions as a diagnostic

- Radiative-capture (n, γ) reactions provide diagnostic for nondestructive assay (NDA) applications
- But is it the most useful γ-ray signature?
- $\sigma_{(n,\gamma)}(E_n = \text{thermal})$ is high; $\sigma_{(n,\gamma)}(E_n > \text{thermal})$ is small
- Can we learn anything from high-energy neutrons?
- Other reaction channels are open
- (n, n') is primary energy-loss mechanism for fast neutrons in heavy nuclei $\Rightarrow$ look for $(n, n'\gamma)$ signatures in NDA

Improved $(n, n'\gamma)$ data needed for accurate simulations of interrogation systems [NDNCA Workshop, LBNL (2015)]

The Baghdad Atlas: $(n, n'\gamma)$ data



- Set of $\sigma_\gamma(E_\gamma)$ relative to 847-keV $2^+_1 \to 0^+_{gs}$ in ^{56}Fe for 105 samples.
- Convolve IRT-500 spectrum with $^{56}\text{Fe}(n, n'\gamma_{847})$ from ENDF-B/VII.1:

$$\langle\sigma\rangle = \frac{\int \phi(E_n)\sigma_\gamma(2^+_1)dE}{\int \phi(E_n)dE} = \frac{\sum \phi(E_n)\sigma_\gamma(2^+_1)\Delta E}{\sum \phi(E_n)\Delta E}$$

- Flux-weighted averages: $\langle\sigma\rangle = 464$ mb; $\langle E_n\rangle = 1.2$ MeV.

No longer accepting beam-time proposals

Development of relational database I

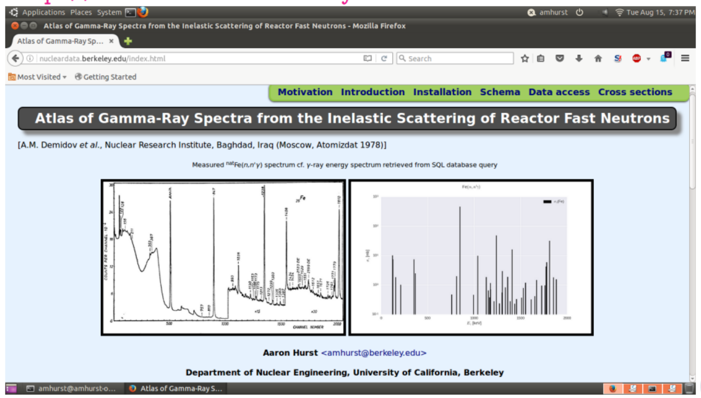
- Serves applications community (nonproliferation, NDA)
- Nuclear data evaluation: benchmarking reaction models in fast-fission neutron-energy range
- Limited use $\Rightarrow$ data *was* only available in printed form
- Data now compiled into a set of CSV-style ASCII tables
- Developed suite of Python scripts and C modules to build SQLite relational database
- Downloadable software platform hosted at:
  National Nuclear Data Center (NNDC)
  http://www.nndc.bnl.gov/lbnlatl.html
  Nuclear Science and Security Consortium (NSSC)
  http://nssc.berkeley.edu/research/nuclear-data/atlas/

Tarball contents

- Approach: Distribute database to expert user community in as general a form as possible
- Source code to build database locally
- Source CSV-style data sets for all 105 samples
- SQL scripts and Jupyter Notebook provided to exemplify methods for retrieving and interacting with the data
- HTML documentation installation instruction and help pages (offline viewing)
- A PDF of the original book by A. M. Demidov *et al.*
- Total package size: $\sim$ 22 Mb

Development of relational database II

http://nucleardata.berkeley.edu



A.M. Hurst, L.A. Bernstein, T. Kawano, A.M. Lewis, K. Song, The Baghdad Atlas: A relational database of inelastic neutron-scattering (n,n′γ) data, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 995, 2021, 165095, https://doi.org/10.1016/j.nima.2021.165095.

Table 2 Prompt gamma rays of calcium, carbon and oxygen induced by fast neutrons on $CaCO_3$

Reaction (E_{thr})	This work				From Demidov Atlas [16]		R
	E_γ (keV)	$(P_{E\gamma}(90°)/\varepsilon_{E\gamma})\times 10^{-8}$ (count)	I_R(relative) (%)	$<\sigma_{E\gamma}(90°)>$ (mb)	E_γ (keV)	I_R(relative) (%)	
$^{40}Ca(n,n'\gamma)^{40}Ca$ (3.44 MeV)	754.41 ± 0.07	0.53 ± 0.03	13.5 ± 0.9	1.45 ± 0.14	755.0 ± 0.4	15 ± 3	−0.48
	1307.49 ± 0.26	0.16 ± 0.03	3.93 ± 0.88	0.42 ± 0.10	–	–	–
	1374.32 ± 0.13[a]	0.36 ± 0.03	8.99 ± 0.89	0.97 ± 0.12	1375.7 ± 1.0	10 ± 2	-0.46
	1876.91 ± 0.19	0.35 ± 0.04	8.78 ± 1.09	0.95 ± 0.13	1877.5 ± 0.9	7.8 ± 1.2	0.61
	2009.76 ± 0.23[b]	0.28 ± 0.04	6.96 ± 0.95	0.75 ± 0.12	–	–	–
	3736.89 ± 0.13	5.28 ± 0.17	133 ± 6	14.3 ± 1.2	3736.9 ± 0.8	123 ± 9	0.93
	3904.76 ± 0.28[c]	3.96 ± 0.14	100	10.8 ± 0.9	3904.2	100	–
$^{42}Ca(n,n'\gamma)^{42}Ca$ (1.56 MeV)	1524.62 ± 0.07	0.87 ± 0.05	22.1 ± 1.4	355 ± 34	1524.4 ± 0.4	20 ± 3	0.63
$^{44}Ca(n,n'\gamma)^{44}Ca$ (1.18 MeV)	726.17 ± 0.11	0.50 ± 0.07	12.5 ± 1.9	46 ± 8	726.3 ± 1.0	12 ± 3	0.14
	1126.03 ± 0.11	0.34 ± 0.03	8.51 ± 0.85	31 ± 4	1125.5 ± 1.0	8.2 ± 2.0	0.14
	1156.78 ± 0.05	3.90 ± 0.14	98 ± 5	359 ± 31	1156.9 ± 0.5	87 ± 6	1.48
	1499.88 ± 0.28	0.21 ± 0.04	5.38 ± 0.93	19.6 ± 3.7	1500.6 ± 0.8	4.6 ± 1.2	0.52
$^{40}Ca(n,p)^{40}K$ (0.54 MeV)	29.78 ± 0.05	63 ± 4[d]	1589 ± 121	171 ± 18	–	–	–
	769.89 ± 0.07[a]	9.56 ± 0.29	241 ± 41	26 ± 2	770.3 ± 0.2	204 ± 10	2.49
	843.54 ± 0.06[a]	0.86 ± 0.15	21.7 ± 3.9	2.34 ± 0.45	–	–	–
	891.19 ± 0.05	1.66 ± 0.07	42 ± 2	4.52 ± 0.41	891.6 ± 0.4	59 ± 7	−2.30
	1158.93 ± 0.10	0.83 ± 0.06	20 ± 2	2.27 ± 0.23	1159.1 ± 0.8	26 ± 4	−1.15
	1247.29 ± 0.16	0.27 ± 0.03	6.77 ± 0.90	0.73 ± 0.11	1247.5 ± 0.6	7.5 ± 2.2	−0.31
	1302.88 ± 0.18	0.27 ± 0.04	6.76 ± 0.93	0.73 ± 0.11	1303.0 ± 0.6	8.1 ± 2.0	−0.61
	1613.58 ± 0.12[a]	0.04 ± 0.01	1.06 ± 0.17	0.11 ± 0.02	–	–	–
	1618.68 ± 0.15	0.39 ± 0.04	9.89 ± 1.08	1.06 ± 0.14	1616.8 ± 1.0[e]	17 ± 4	−1.72
	1929.02 ± 0.22	0.17 ± 0.03	4.29 ± 0.66	0.46 ± 0.08	1929.2 ± 1.6	6.1 ± 1.0	−1.51
	2007.13 ± 0.30	0.22 ± 0.04	5.43 ± 0.92	0.58 ± 0.11	2007.8 ± 0.9[f]	8.3 ± 1.3	−1.80
	2017.39 ± 0.21[a]	0.17 ± 0.05	4.40 ± 1.20	0.47 ± 0.13	2017.8 ± 0.9	5.8 ± 1.2	−0.82
	2039.49 ± 0.19	0.38 ± 0.04	9.68 ± 1.00	1.04 ± 0.13	2040.4 ± 1.0	8.0 ± 1.3	1.02
	2046.72 ± 0.24	0.29 ± 0.04	7.43 ± 0.95	0.80 ± 0.12	2047.8 ± 1.5	4.8 ± 1.1	1.81
	2069.85 ± 0.30	0.32 ± 0.04	7.99 ± 1.15	0.86 ± 0.14	2068.3 ± 1.6	6.0 ± 1.2	1.20
	2073.55 ± 0.12[a]	0.45 ± 0.08	11.3 ± 2.1	1.22 ± 0.24	2073.4 ± 1.0	13 ± 2	−0.57
	2289.66 ± 0.21[g]	0.28 ± 0.02	6.95 ± 0.67	0.75 ± 0.09	2289.8 ± 1.2	11 ± 2	−1.92
	2366.25 ± 0.50	0.18 ± 0.04	4.54 ± 0.98	0.49 ± 0.11	2366.6 ± 2.0	4.8 ± 1.0	−0.19
	2545.64 ± 0.27	0.52 ± 0.06	13.2 ± 1.5	1.42 ± 0.19	2545.1 ± 1.0	14 ± 2	−0.31
	3683.79 ± 0.37	0.16 ± 0.03	4.15 ± 0.71	0.45 ± 0.08	–	–	–
$^{40}Ca(n,\alpha)^{37}Ar$ (0 MeV)	1409.61 ± 0.10[a]	0.74 ± 0.04	18.8 ± 1.1	2.02 ± 0.19	1409.8	21 ± 3	−0.70
	1611.24 ± 0.08	1.65 ± 0.07	42 ± 2	4.47 ± 0.40	1611.2 ± 0.6[h]	48 ± 5	−0.95
	2490.24 ± 0.27	0.17 ± 0.03	4.41 ± 0.73	0.47 ± 0.08	2490.0 ± 1.0	9 ± 2	−2.16
$^{12}C(n,n'\gamma)^{12}C$ (4.81 MeV)[j]	4441.14 ± 0.42[a,c]	5.39 ± 1.14	100	14.4 ± 3.3	4438 ± 2	109[i]	–
$^{16}O(n,n'\gamma)^{16}O$ (6.43 MeV)[j]	6129.32 ± 0.22[a]	2.50 ± 0.37	547 ± 121	2.20 ± 0.37	6129.3 ± 1.0	595 ± 120	−0.28
$^{18}O(n,n'\gamma)^{18}O$ (6.43 MeV)[j]	1981.69 ± 0.18	0.46 ± 0.05	100	201 ± 28	1983.0 ± 0.4	100	–

73-rd Int. conf. on nuc. physics "Nucleus-2023: Fundamental problems and applications", 9-13 Oct. 2023, Sarov, Russia

2023 ЯДРО

Yields of γ-quanta emitted by calcium during 14.1 MeV neutrons irradiation

Fedorov N.A. * , Grozdanov D.N., Kopatch Yu.N., Skoy V.R., Tretyakova T.Yu., Hramco K., Ruskov I.N., Akhmedov G., Berikov D., Andreev A.V., Filonchik P.G. and "TANGRA" collaboration
nfedorov@jinr.ru

E, keV	Y	Talys	Simakov	E_i keV, J^P_i	E_f keV, J^P_f	Reaction
754,7397	56±3	30,1	63±3	4491,4 (5^-)	3736,7 (3^-)	$^{40}Ca(n,n')^{40}Ca$
770,313	107±4	44,2		800,1 (2^-)	29,8 (3^-)	$^{40}Ca(n,p)^{40}K$
891,398	88±6	32,8	46±3	891,4 (5^-)	0 (4^-)	$^{40}Ca(n,p)^{40}K$
1157,019		11,3	25±3	1157 (2^+)	0 (0^+)	$^{44}Ca(n,n')^{44}Ca$
1158,925	38±6	8,4		1959,1 (2^+)	800,1 (2^-)	$^{40}Ca(n,p)^{40}K$
1374,42	10±2	9,6		5278,8 (4^+)	3904,4 (2^+)	$^{40}Ca(n,n')^{40}Ca$
1409,84	16±2	14,7		1409,8 $(1/2^+)$	0 $(3/2^+)$	$^{40}Ca(n,\alpha)^{37}Ar$
1611,28		48,2	57±2	1611,3 $(7/2^-)$	0 $(3/2^+)$	$^{40}Ca(n,\alpha)^{37}Ar$
1613,809	20±4	7,5		1643,6 (0^+)	29,8 (3^-)	$^{40}Ca(n,p)^{40}K$
2217	34±8	19,8		2217 $(7/2^+)$	0 $(3/2^+)$	$^{40}Ca(n,\alpha)^{37}Ar$
2230,57	8±3	5,6		2260,4 (3^+)	29,8 (3^-)	$^{40}Ca(n,p)^{40}K$
2796,15	19±10	12,5	30±1	2796,1 $(5/2^+)$	0 $(3/2^+)$	$^{40}Ca(n,\alpha)^{37}Ar$
2814,3	14±7	37,6		2814,3 $(7/2^-)$	0 $(3/2^+)$	$^{40}Ca(n,d)^{39}K$
3736,69	100,0	100,0	100,0	3736,7 (3^-)	0 (0^+)	$^{40}Ca(n,n')^{40}Ca$
3904,38	31±7	34,9	41±2	3904,4 (2^+)	0 (0^+)	$^{40}Ca(n,n')^{40}Ca$
5629,41	15±5	3,3		5629,4 (2^+)	0 (0^+)	$^{40}Ca(n,n')^{40}Ca$

Nuclear Structure Studies (NSS) with the Inelastic Neutron Scattering (INS) Reaction and Gamma-Ray Detection (GRD)

At relatively low incident-neutron energies, the INS reaction occurs predominantly through the ***compound nucleus mechanism** (**CNM**)*, similar to fusion-evaporation reactions with charged particles. Therefore, the reaction leads to an ***alignment** of the excited nuclei*, so the **γ-ray angular distributions** from the decays of the excited levels exhibit ***anisotropies** reflecting this alignment, the **spins** of the levels, and the **multipolarities** of the transitions.*

The levels with lifetimes in the range from **~10 fs to ~10 ps** can be investigated in **(n,n'γ) measurements** by employing the **Doppler-Shift Attenuation Method (DSAM)**

(Alexander T.K., Forster J.S., Lifetime Measurements of Excited Nuclear Levels by Doppler-Shift Methods., (1978) In: Baranger M., Vogt E. (eds) Advances in Nuclear Physics. Springer, Boston, MA, https://doi.org/10.1007/978-1-4757-4401-9_3)

Lifetime data for low-spin states have been obtained using the **Doppler-Shift Attenuation Method following the *Inelastic neutron scattering reaction* (DSAM-INS)**, developed and extensively used at the University of Kentucky

(T. Belgya, G. Molnár, S.W. Yates, Analysis of Doppler-shift attenuation measurements performed with accelerator-produced monoenergetic neutrons   Nucl. Phys. A 607 (1996) 43, https://doi.org/10.1016/0375-9474(96)00221-7

P. E. Garrett, N. Warr and S. W. Yates, J. Res. Natl. Inst. Stand. Technol. 105, 141 (2000), https://pdfs.semanticscholar.org/7094/e01ed283fbb91bb2972d739bac4c3724c419.pdf

ENSDF | Evaluated Nuclear Structure Data File: ^{40}Ca

Dataset	Last Revised	References
Select All		
ADOPTED LEVELS, GAMMAS	2017-02	All references
40K B- DECAY (1.248E+9 Y)	2017-02	All references
40SC EC DECAY (182.3 MS)	2017-02	All references
41TI ECP DECAY (80.4 MS)	2017-02	All references
43CR B+3P DECAY (21.2 MS)	2017-02	All references
44V ECA DECAY (111 MS)	2017-02	All references
INELASTIC SCATTERING	2017-02	All references
4HE(36AR,A):RESONANCES	2017-02	All references
14N(28SI,D)	2017-02	All references
32S(12C,A)	2017-02	All references
36AR(A,G):RESONANCES	2017-02	All references
36AR(6LI,D)	2017-02	All references
36AR(7LI,T)	2017-02	All references
36AR(16O,12C)	2017-02	All references
38AR(3HE,N)	2017-02	All references
39K(P,G)	2017-02	All references
39K(P,P),(P,A):RESONANCES	2017-02	All references
39K(D,N)	2017-02	All references
39K(3HE,D)	2017-02	All references
39K(3HE,DG)	2017-02	All references
40CA(G,G')	2017-02	All references
40CA(E,E')	2017-02	All references
40CA(PI+,PI+'),(PI-,PI-')	2017-02	All references
40CA(N,N'),(POL N,N')	2017-02	All references
☑ 40CA(N,N'G)	2017-02	All references
40CA(P,P'G)	2017-02	All references
40CA(P,PA),(P,2P):RESONANCES	2017-02	All references
40CA(D,D'),(POL D,D')	2017-02	All references
40CA(T,T),(POL T,T)	2017-02	All references
40CA(3HE,3HE')	2017-02	All references
40CA(A,A')	2017-02	All references
40CA(A,A'G)	2017-02	All references
41CA(D,T)	2017-02	All references
41CA(3HE,A)	2017-02	All references
42CA(P,T)	2017-02	All references
42CA(16O,18O)	2017-02	All references
(HI,XNG)	2017-02	All references

References quoted in the ENSDF dataset: ^{40}Ca(n, n'γ) - 7 references found.

1963HO08
Z.Phys. 173, 402 (1963): A.Hofmann, γ-Strahlung bei Inelastischer Streuung von 14 MeV Neutronen an Calcium, Sauerstoff und Kohlenstoff, NUCLEAR STRUCTURE 12C, 16O, 40Ca; measured not abstracted; deduced nuclear properties.

1966MA10
Nucl.Phys. 81, 468 (1966), S.C.Mathur, P.S.Buchanan, I.L.Morgan, Angular Distributions of Gamma Rays in (n, n'γ) Reactions as a Basis for Nuclear Level Spins, NUCLEAR STRUCTURE 89Y, 26Mg, 27Al, 24Mg, 208Pb, 40Ar, 40Ca, 28Si, 59Co, 56Fe, 54Fe; measured not abstracted; deduced nuclear properties.

1972DI10
Nucl.Sci.Eng. 48, 78 (1972), J.K.Dickens, The Neutron Induced Gamma-Ray Reactions in Calcium in the Energy Range 4.85 < E < 8.05 MeV, NUCLEAR REACTIONS 40Ca(n, n'γ), (n, pγ), (n, αγ), E=4.85-8.05 MeV; measured σ(E;Eγ).

1972NI05
Can.J.Phys. 50, 553 (1972), L.Nichol, T.J.Kennett, Inelastic Neutron Scattering in the Region A = 11-40, NUCLEAR REACTIONS 11B, 14N, 19F, 23Na, 27Al, 28Si, 40Ca(n, n'γ), E=fission spectrum; measured σ(Eγ). 11B, 14N, 19F, 23Na, 27Al, 28Si, 40Ca deduced levels, J, π, γ-branching. Ge(Li), NaI(Tl) detectors.

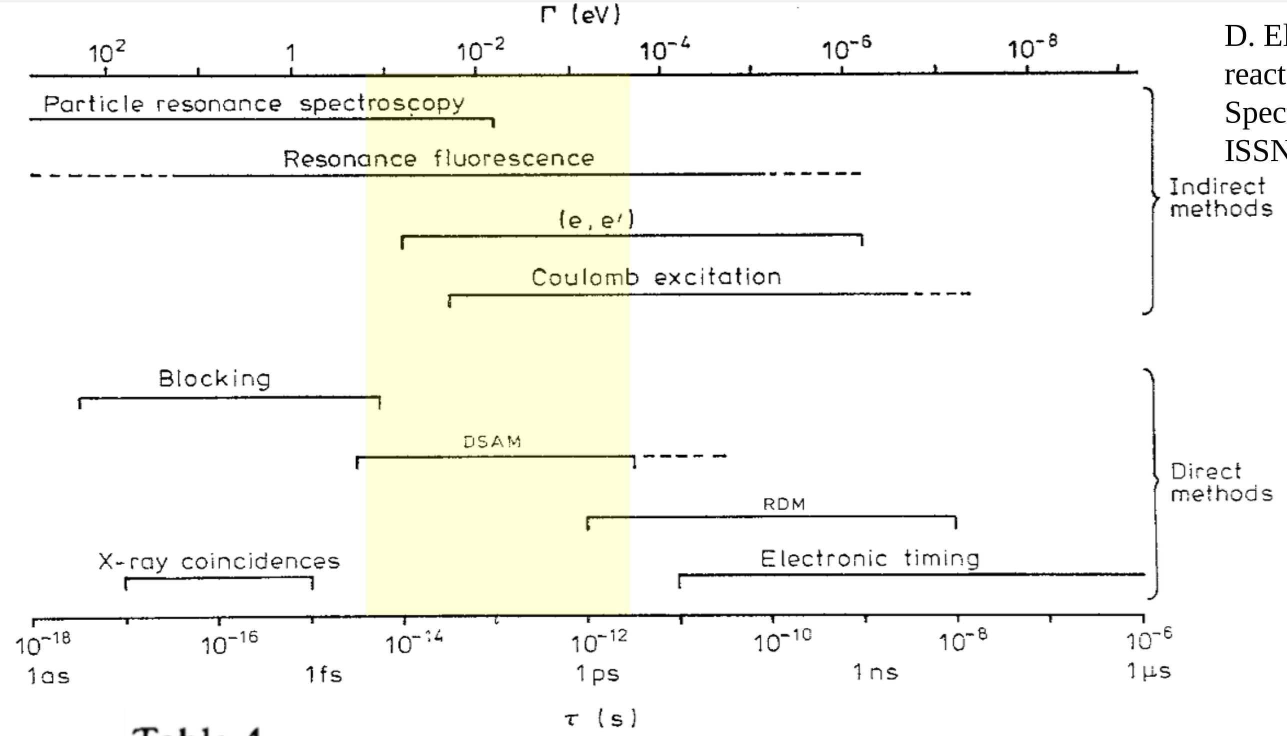
1981KAZL
Program and Theses, Proc.31st Ann.Conf.Nucl.Spectrosc.Struct.At.Nuclei, Samarkand, p.54 (1981), D.K.Kaipov, Yu.G.Kosyak, Yu.A.Lysikov, NUCLEAR REACTIONS Ca(n, n'γ), E=fast; measured Eγ, Iγ, DSA. 40,44Ca levels deduced T1/2. Natural targets.

1984EL12
Nucl.Instrum. Methods 228, 62 (**1984**), D. Elenkov, D. Lefterov, G. Toumbev, Two-Target **DSAM** following the **(n, n'γ)** Reaction with Fast Reactor Neutrons, NUCLEAR REACTIONS 11B, 24Mg, 27Al, 32S, 35Cl, 39K, 40Ca, 45Sc, 51V(n, n'γ), E=fast; measured DSA. 11B, 24Mg, 27Al, 32S, 35Cl, 39K, **40Ca**, 45Sc, 51V levels deduced T1/2. Two-target system.

1989GE09
Fiz.Elem.Chastits At.Yadra 20, 930 (**1989**); Sov. J. Part .Nucl. 20, 393 (1989), M.K. Georgieva, D.V. Elenkov, D.P. Lefterov, G.H. Toumbev, Measurement of the Lifetimes of Excited Nuclear States by the **Doppler Shift Attenuation Method** Using the Reaction **(n, n'γ)** with Two Targets, NUCLEAR REACTIONS 11B, 23Na, 24Mg, 27Al, 28Si, 31P, 32S, 35,37Cl, 39K, 40Ca, 45Sc, 48Ti, 51V, 52Cr, 55Mn, 56Fe, 58,60,64Ni(n, n'γ), E=fast; measured γ-spectra, DSA. 11B, 23Na, 24Mg, 27Al, 28Si, 31P, 32S, 35,37Cl, 39K, **40Ca**, 45Sc, 48Ti, 51V, 52Cr, 55Mn, 56Fe, 58,60,64Ni level deduced T1/2, B(λ).

https://www.nndc.bnl.gov/ensdf/getrefs.jsp?recid=40020021&dsid=40CA(N,N%27G)

Determine Excited Nuclear State Lifetime Using DSAM



D. Elenkov, D. Lefterov, G. Toumbev, Two-target DSAM following the (n,n′γ) reaction with fast reactor neutrons, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 228, Issue 1, **1984**, Pages 62-68, ISSN 0168-9002, https://doi.org/10.1016/0168-9002(84)90011-1.

1984

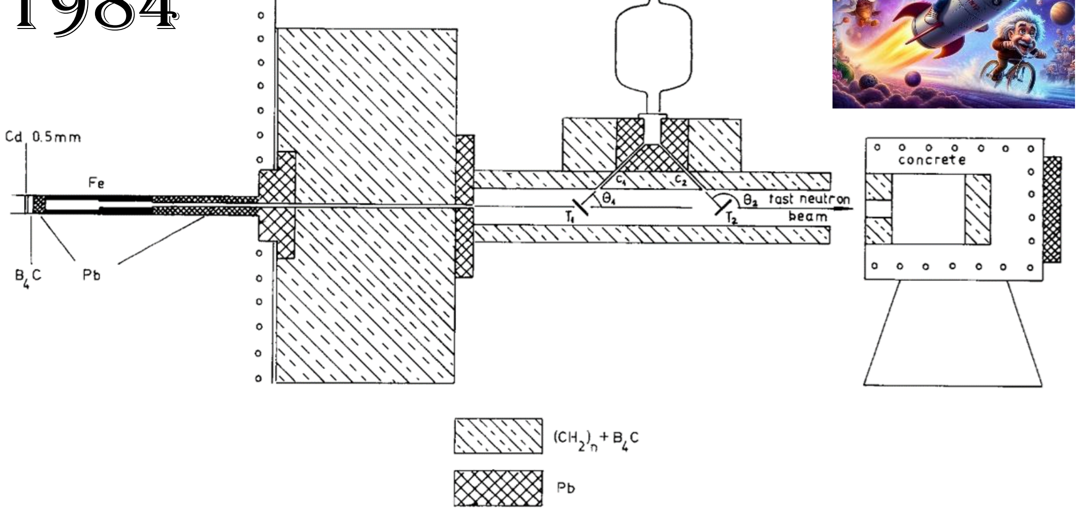


Fig. 1. Two-target experimental arrangement for DSAM after a (n, n′γ) reaction with reactor fast neutrons.

Table 4
Mean lifetime results obtained by DSAM following the (n,n′γ) reaction.

	E^{state} (keV)	Mean lifetime τ (10^{-14} s)	*ref. [25]*	*ref. [26]*	*ref. [5]*
^{40}Ca	3904	5.2 ± 2.0	5.4 ±0.6	5.8 ± 1.0	5.4±0.2

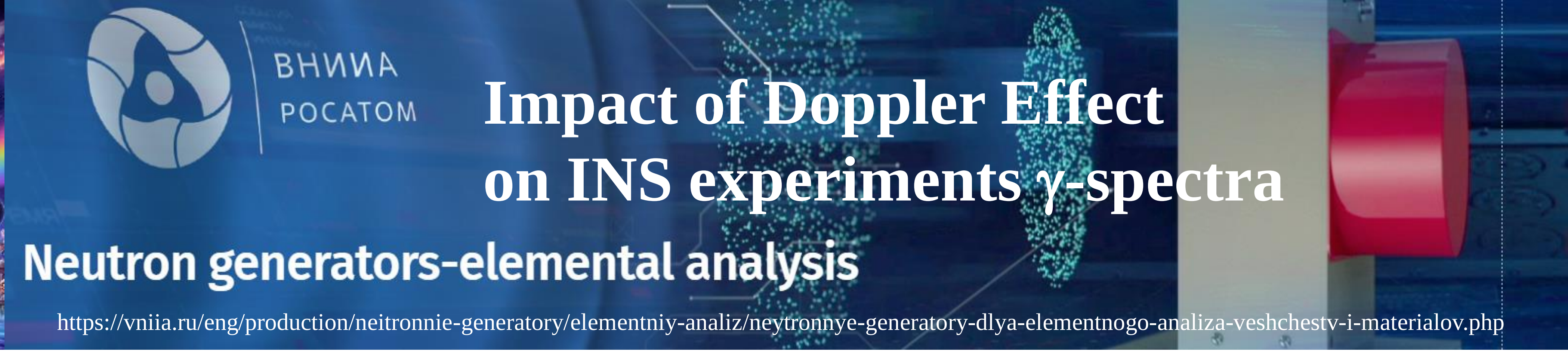
Георгиева М. К., Еленков Д. В., Лефтеров, Измерение времени жизни возбужденных состояний ядер методом ОДС в реакции (n, n'γ) с двумя мишенями, http://www1.jinr.ru/Archive/Pepan/1989-v20/v-20-4/pdf_obzory/v20p4-4.pdf

Jun Chen, Nuclear Data Sheets for A=40, Nuclear Data Sheets, Volume 140, 2017, Pages 1-376, ISSN 0090-3752, https://doi.org/10.1016/j.nds.2017.02.001.

P. J. Nolan and J. F. Sharpey-Schafer, The measurement of the lifetimes of excited nuclear states, https://iopscience.iop.org/article/10.1088/0034-4885/42/1/001/pdf

[5] P.J. Endt and C. Van der Leun, Nucl. Phys. A214 (1973) 1.
[25] R.A. Eisenstein, D.W. Madsen, H. Theissen, L.S. Cardman and C.K. Bockelman, Phys. Rev. 188 (1969) 1815.
[26] J.R. McDonald, D.H. Willkinson and D.E. Alburger, Phys.Rev. C3 (1971) 219.

Impact of Doppler Effect on INS experiments γ-spectra

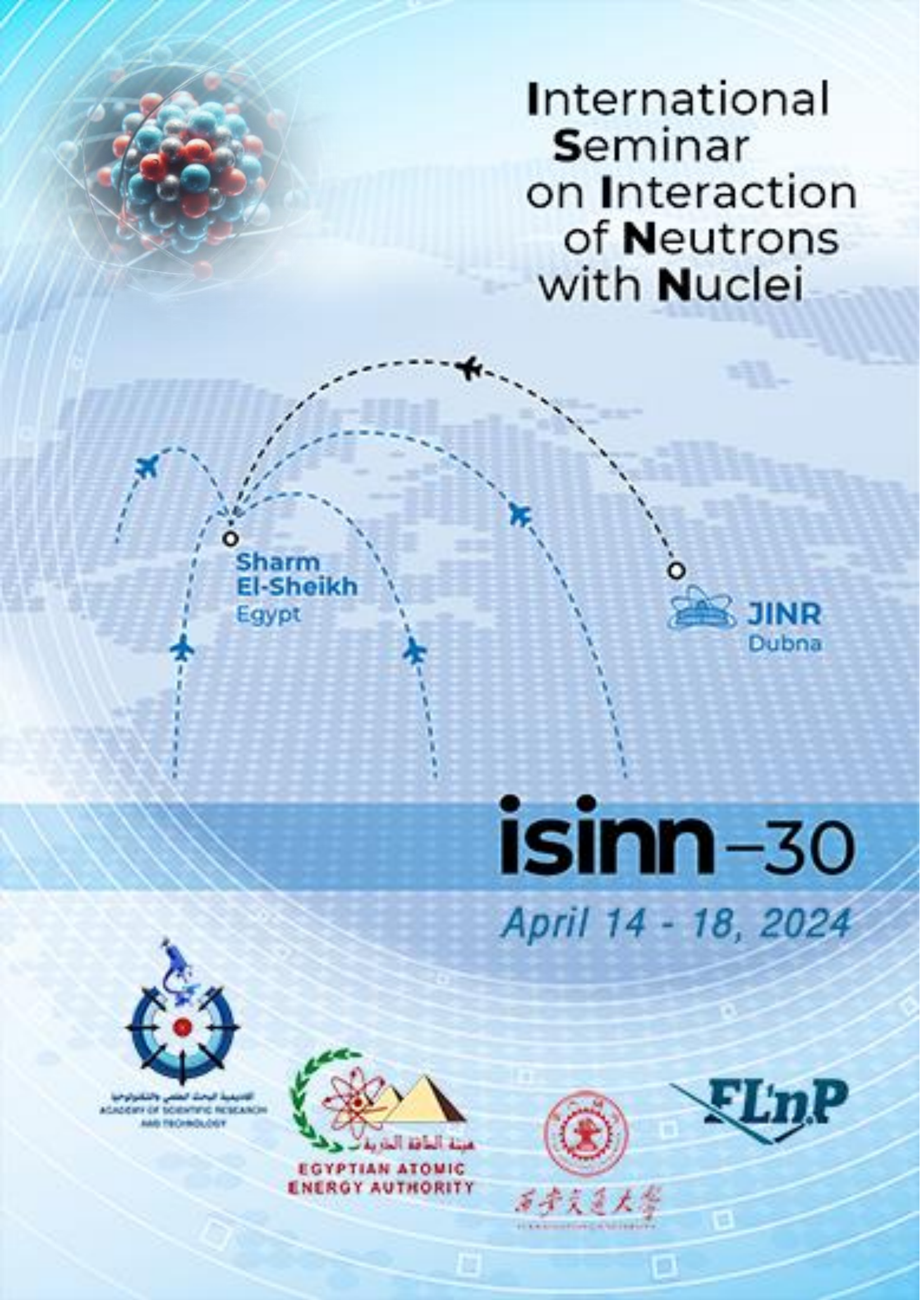


Batyaev, V.F., Belichenko, S.G., Karetnikov, M.D. *et al.* Energy−Angular Correlations at Inelastic Scattering of Tagged Neutrons by *Carbon*, *Nitrogen*, and *Oxygen* Nuclei. *Instrum Exp Tech* **66**, 523–530 (**2023**). https://doi.org/10.1134/S0020441223030168

The accuracy of elemental analysis in bulk samples using 14-MeV tagged neutron methods depends heavily on precise measurements of γ-ray spectrum peak parameters. Addressing the Doppler effect, which causes shifts and broadening of γ-ray peaks, and considering the anisotropy of γ-ray yield concerning the angle between tagged neutrons and detected γ-rays, is crucial. In this study, the authors explore the angular dependencies of shift and intensity (relative area) of γ-ray spectrum peaks for carbon, nitrogen, and oxygen nuclei. This effect becomes more pronounced in bulk samples and setups with multiple γ-detectors, where γ-rays interact with detectors at various angles relative to the tagged neutron direction.

Belichenko, S.G., Karetnikov, M.D. & Maznitsyn, A.D. Impact of the Doppler Effect on the Spectra of Gamma Rays in Inelastic Scattering of Tagged Neutrons by *Carbon* and *Nitrogen* Nuclei. *Phys. Atom. Nuclei* **85**, 1920–1924 (**2022**). https://doi.org/10.1134/S1063778822100076

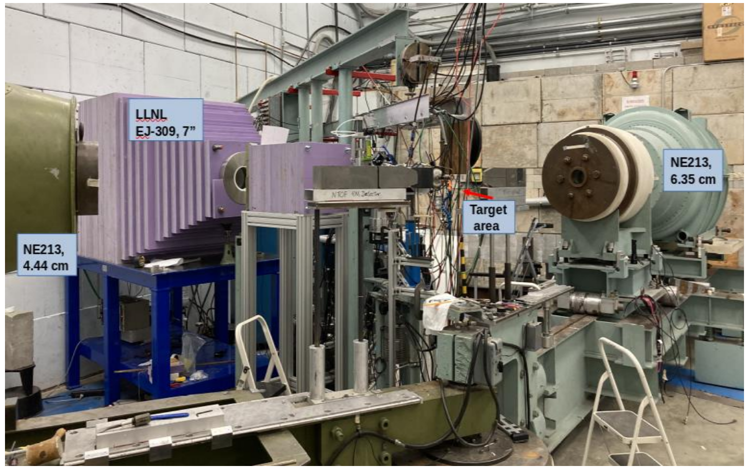
Determining elemental composition via investigation of characteristic gamma spectra from inelastic scattering of 14-MeV tagged neutrons on irradiated sample nuclei relies on accurate gamma-ray energy determination (a ~1% error leads to ~10% abundance error). Significant Doppler effect impact (broadening and shift of gamma lines) observed, particularly for carbon and nitrogen nuclei.


International
Seminar
on Interaction
of Neutrons
with Nuclei
Sharm
El-Sheikh
Egypt
JINR
Dubna
isinn–30
April 14 - 18, 2024
EGYPTIAN ATOMIC
ENERGY AUTHORITY
FLnP

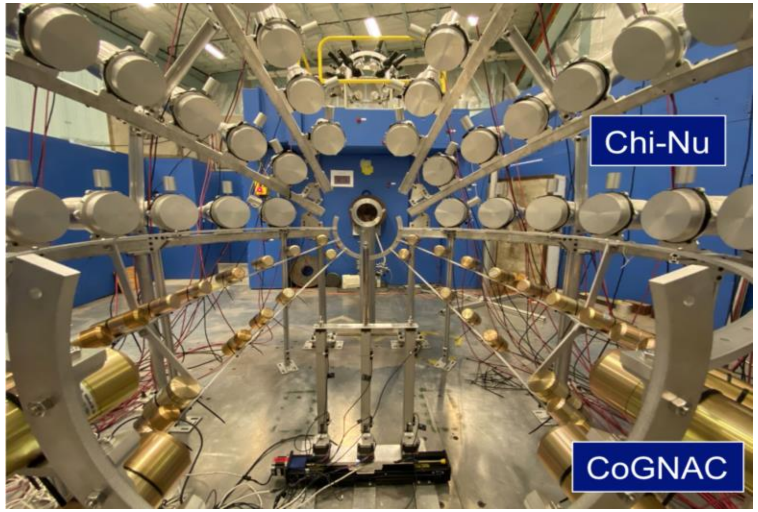

Thank you
for your attention!
НАРОДНА БИБЛИОТЕКА КИРИЛ И МЕТОДИЙ
Interaction of
14-MeV neutrons
with ^{40}Ca
EGYPTIAN ATOMIC
ENERGY AUTHORITY
FLnP

Neutron scatter measurements have been identified as a priority

- Scattering is a difficult neutron reaction channel to measure and poorly constrained
  - Limited reaction observables: neutrons, γ rays
  - Neutrons are very hard (but necessary) to measure, generally rely on time-of-flight for energy measurement (>>10 ns flightpath)
- Actinides present more obstacles:
  - Significant neutron background from fission
  - Low γ-ray energies/intensities in actinides make neutrons the only reliable probe
  - Actinide material difficult to work with
- Active efforts underway to collect these important data



Monoenergetic neutron source: LLNL with TUNL



Broad-energy neutron source: LANL at LANSCE with CoGNAC

CoGNAC: $^{12}C(n,n'\gamma)$; $^{6}Li(n,n'\gamma)$; $^{7}Li(n,n'\gamma)$

The Neutron Scattering Cross Section and Angular Distribution Measurement Program at LANL

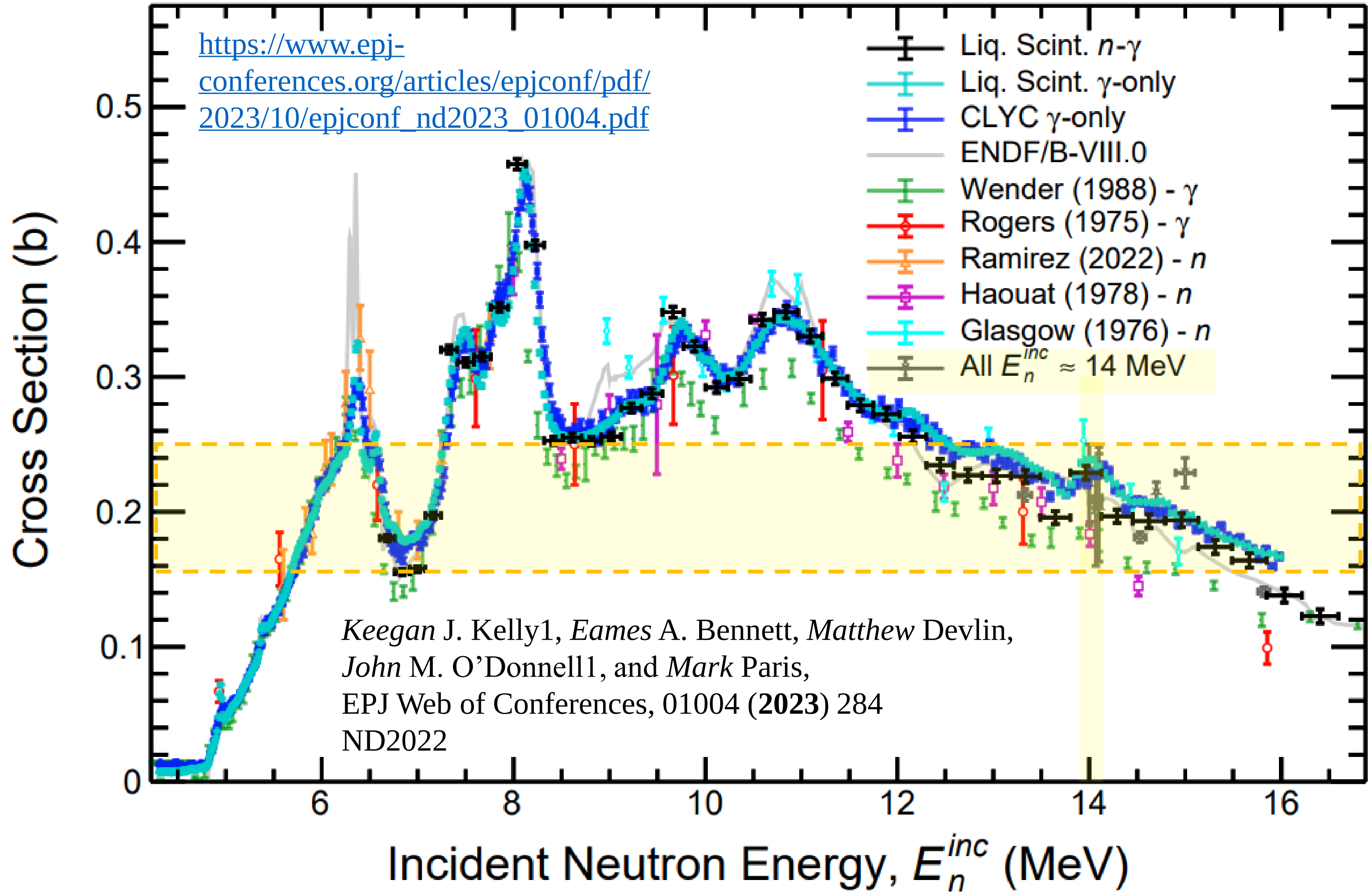
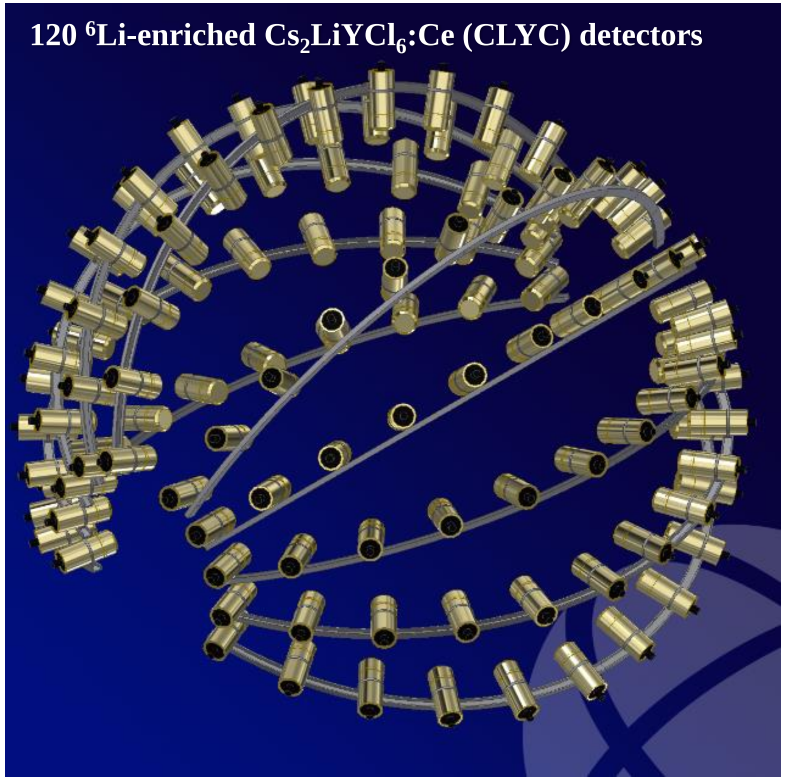


Figure 7: Preliminary results for the $^{12}C(n,n'\gamma)$ cross section populating the 4.4398 MeV first excited state. The present data are shown in black. Preliminary γ-only data collected with the same liquid scintillator detectors described in the work are shown in cyan here as well. See Sec. 5 for a discussion of the data labeled "CLYC γ-only."



An emerging program at Los Alamos National Laboratory for measurements of neutron scattering cross sections and neutron, γ-ray, and correlated n-γ angular distributions utilizing liquid scintillator detectors and the **Correlated Gamma-Neutron Array for Scattering (CoGNAC) of CLYC scintillators**.

Recent measurements on carbon have also shown definitive proof that the neutron angular distribution can change with respect to the emission angle of γ-rays from inelastic scattering, thereby complicating γ-tagged measurements of inelastic neutron scattering.

The **correlated n-γ distributions** from the Q = 4.4398 MeV ^{12}**C(n, n'γ)** reaction are limited to three measurements at incident neutron energies near 14 MeV: Benetski *et al.* [1], Zamudio *et al.* [2], Spaargaren *et al.* [3].

The work of Kelly *et al.* [4] describe a measurement of the n, γ, and correlated n-γ angular distributions from the Q = 4.4398 MeV ^{12}C(n, n'γ) reaction in a single experiment using an EJ-309 liquid scintillator detector array with wide angular coverage, and with a continuous incident neutron energy range from 6.5–16.5 MeV.

Their results do not generally agree with any of these literature measurements.
They observe clear indications of significant changes in the n-distribution for specific γ-detection angles and vice versa especially near thresholds for other reaction channels, which shows the potential for significant bias in experiments that, for example, tag on inelastic scattering using a single or small number of γ-detection angles and could impact particle transport calculations.

[1] B.A. Benetskii and I.M. Frank, Angular Correlation Between Gamma Rays and 14-MeV Neutrons Scattered Inelastically by Carbon, Sov. Phys. JETP 44, 454 (**1963**). http://www.jetp.ras.ru/cgi-bin/dn/e_017_02_0309.pdf

[2] J. Zamudio, L. Romero, R. Morales, Angular correlation measurements of 12C(n, n′γ)12C at 14.7 MeV, Nuclear Physics A, Volume 96, Issue 2, **1967**, Pages 449-462, https://doi.org/10.1016/0375-9474(67)90726-9.

[3] D. Spaargaren, C.C. Jonker, Angular correlations in inelastic neutron scattering by carbon at 15.0 MeV, Nuclear Physics A,Volume 161, Issue 2, **1971**, Pages 354-374, https://doi.org/10.1016/0375-9474(71)90374-5.

[4] K.J. Kelly, M. Devlin, J.M. O'Donnell, and E. A. Bennett, Correlated n-γ Angular Distributions from the Q = 4.4398 MeV ^{12}C(n,n'γ) Reaction for Incident Neutron Energies from 6.5–16.5 MeV, Phys. Rev. C104, **2021**,064614, https://laro.lanl.gov/view/pdfCoverPage?instCode=01LANL_INST&filePid=13163455700003761&download=true https://doi.org/10.1103/PhysRevC.104.064614.

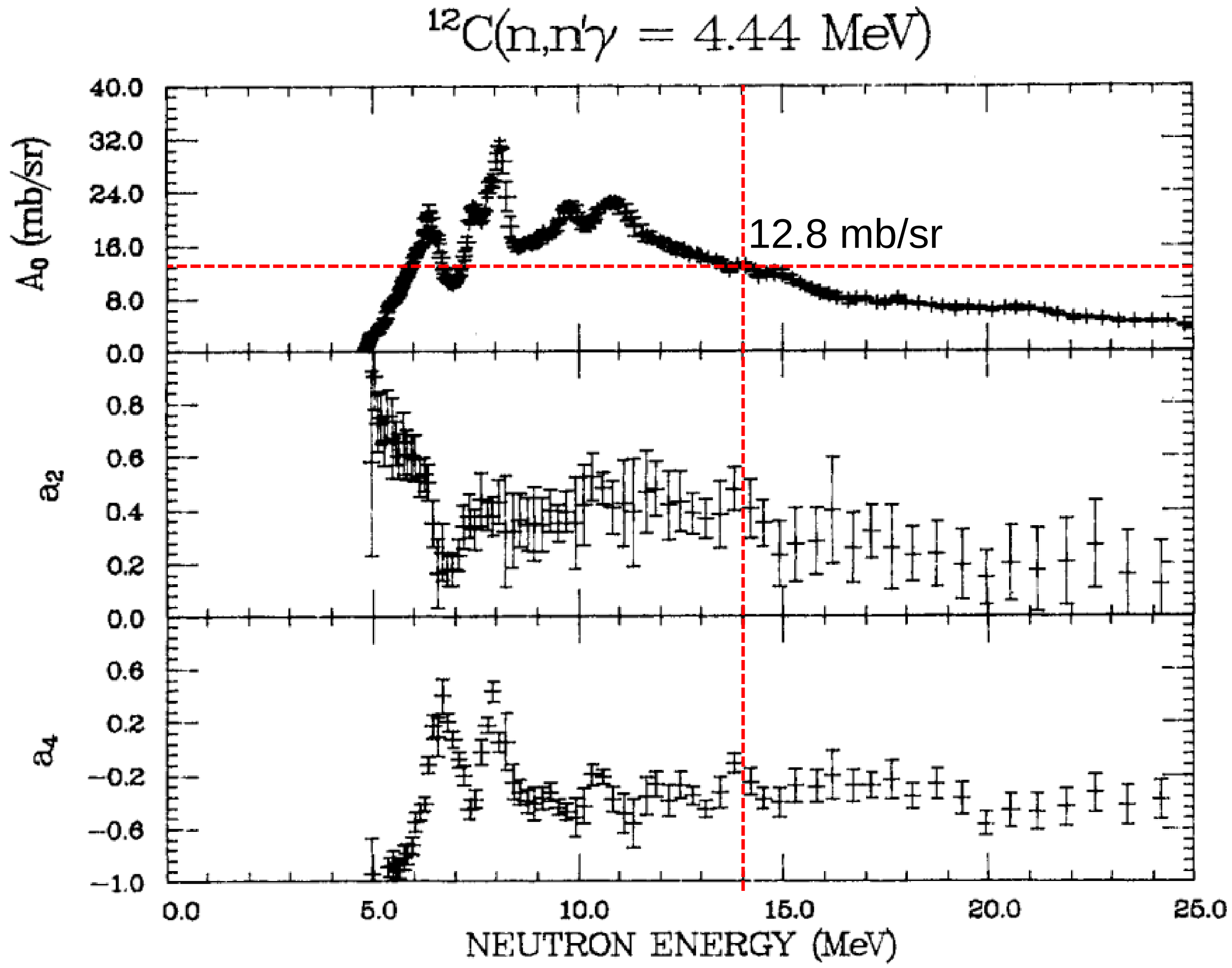


Figure 5. The cross section, the a_2 coefficient, and the a_4 for the production of 4.44 MeV gamma-rays as a function of neutron energy.

S. A. Wender, S. J. Seestrom-Morris, and R. O. Nelson, A white neutron source from 1 to 400 MeV, J. Phys. G: Nucl. Phys. 14, S417 (**1988**). https://doi.org/10.1088/0305-4616/14/S/041

The neutrons are produced in a spallation reaction using the 800 MeV pulsed proton beam from the Los Alamos Meson Physics Facility (LAMPF) accelerator.

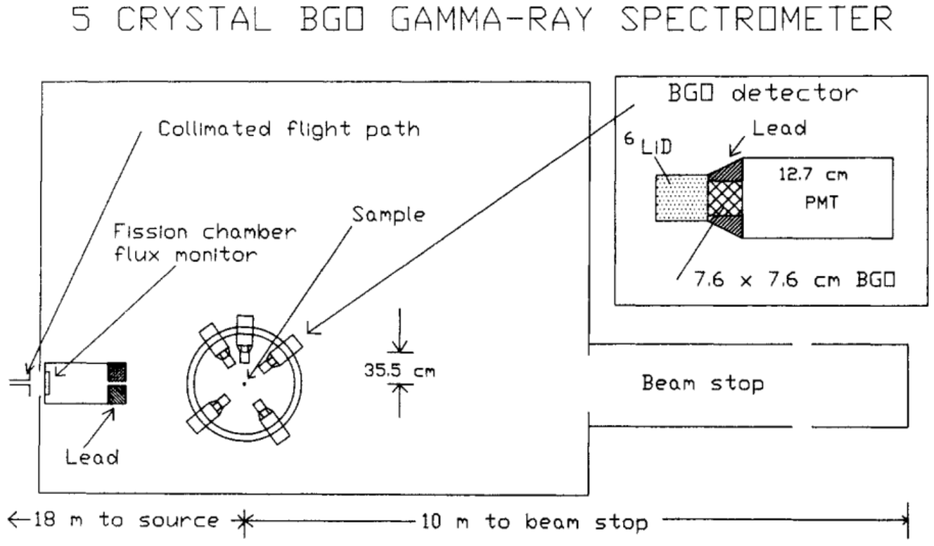


Figure 4. A plan view of the gamma-ray detector for use on the 15^0 18 m flight path at target-4.

It consists of five 7.6-cm diameter and 7.6-cm long BGO scintillators located at 40", 55", 90", 125", and 140" with respect to the incident neutron beam in the reaction plane.

The data of Wender et al. definitively suggest a significant a4 Legendre polynomial coefficient, which creates the decrease in the angular distribution towards extreme forward and backward angles. The ENDF/B-VIII.0 evaluation does not appear to incorporate this component, and as a result the angular distribution from Wender et al. strongly disagrees with ENDF/B-VIII.0 at these extreme angles.

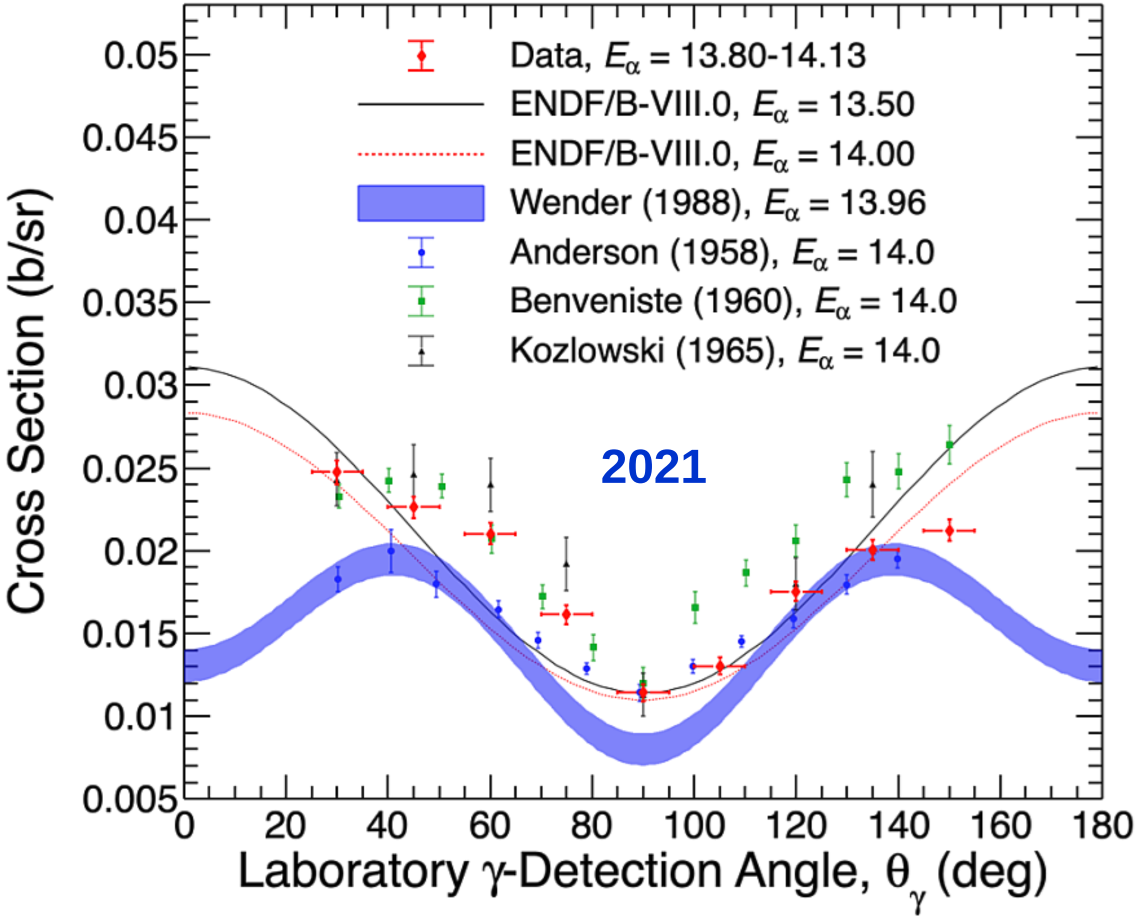
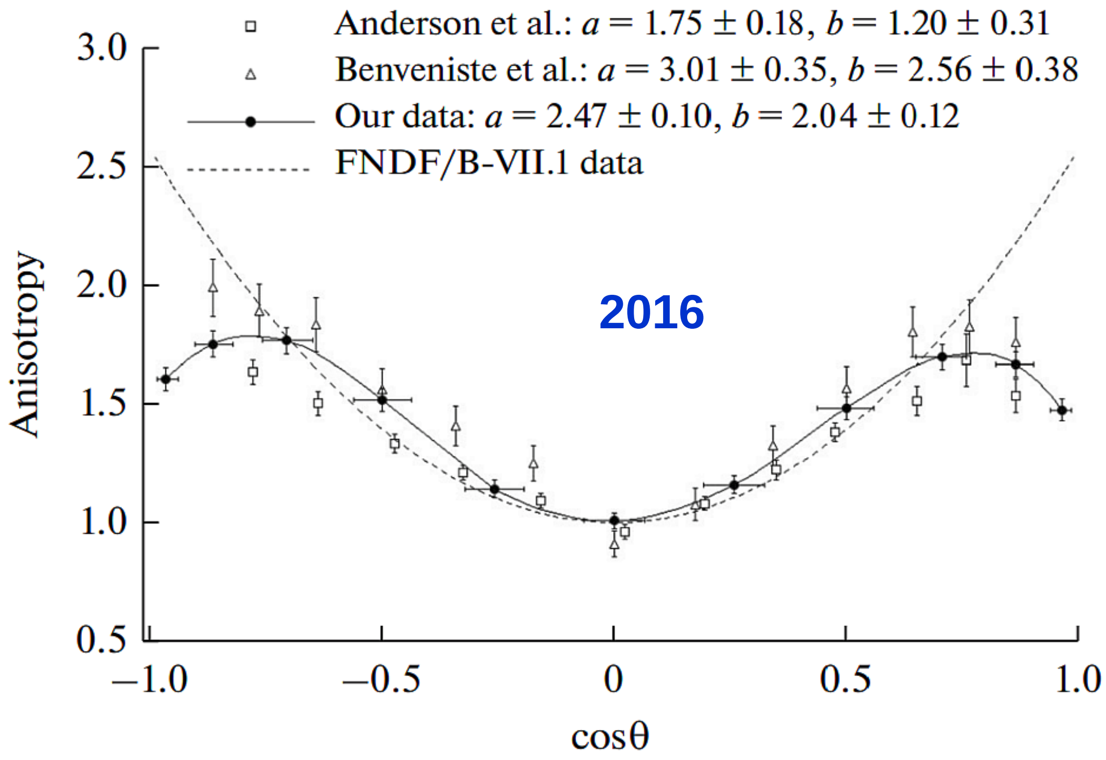


FIG. 11: Results for normalized γ distributions are shown 13.80–14.13 MeV in panel (e), All Eα values are in MeV. The present results are scaled to ENDF/B-VIII.0 evaluation as described in the text.



Bystritsky, V.M., Grozdanov, D.N., Zontikov, A.O. *et al.* Angular distribution of 4.43-MeV γ-rays produced in inelastic scattering of 14.1-MeV neutrons by ^{12}C nuclei. *Phys. Part. Nuclei Lett.* **13**, 504–513 (2016). https://doi.org/10.1134/S154747711604004X

The next step of the planned physical program is to measure the angular correlations between the directions of the escape of neutrons and γ-rays produced in the reaction from the target.

In fact, all other literature data sets shown at $E_\alpha \approx 14$ MeV also show some signature of this same decrease in the angular distribution at towards extreme angles. Considering these facts, **it seems likely that a nonzero a_4 component for the γ-distributions from this reaction is more realistic than the distributions currently existing in ENDF/B-VIII.0.**